Installation, Operation, and Maintenance Costs for Distributed Generation Technologies

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Technical Report

Installation, Operation, and Maintenance Costs for Distributed Generation Technologies

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PRODUCT DESCRIPTION

Distributed generation (DG) is a broad term that encompasses both mature and emerging onsite power generation technologies with power output as small as 1 kW and as large as 20 MW. While the equipment or purchase cost of a DG system is very important, installation, operation, and maintenance (IOM) costs also are significant and often overlooked. This report reviews IOM costs for both mature and emerging DG technologies. Some equipment cost data are included for reference, but are not the focus of this report.

IOM costs for emerging microturbines and fuel cells are relatively high and unpredictable compared to more mature DG systems like internal combustion (IC) engines and combustion turbines. However, as microturbines and fuel cells approach full-scale commercialization, it is expected that IOM costs will decline and become more consistent with mature technologies. Factors that will contribute to lower IOM costs and higher predictability include

- Increased population of trained installation and maintenance personnel
- Increased competition between companies that install and maintain equipment
- Well-developed and uniform standards that govern installation requirements
- Improved reliability of equipment as delivered by manufacturers

The detailed IOM costs in this report will help EPRI members make informed decisions for business planning or selecting DG technologies for a given application.

Results & Findings

IOM costs are a significant part of an overall distributed generation project. Often, many aspects of IOM costs are overlooked or left out of installed cost estimates. IOM costs also can vary significantly due to many factors, including equipment size, local labor rates, technology add-ons (for example, heat recovery), and others. This report reviews and characterizes 2002 IOM costs for IC engines, small combustion turbines, microturbines, and fuel cells.

IC engines generally have the lowest installation costs for DG technologies, followed closely by combustion turbines. Microturbines and fuel cells tend to have much higher installation costs. Data in this report are primarily from actual installations and are intended to reflect real and current costs. Any projected or estimated cost data are clearly identified.

Challenges & Objectives

This report deals with IOM costs of DG technologies and has the following objectives:

- Characterize current IOM costs for IC engines, combustion turbines, microturbines, and fuel cells.

- Speculate how IOM costs for emerging DG technologies may decline as these products become widely deployed by comparing them to equipment in mature industries (for example, heating, ventilating, and air conditioning, or HVAC, and diesel backup gensets).

The most significant challenge with this type of analysis is obtaining reliable data. Manufacturers and installers are reluctant to provide this type of information because of competitive concerns. Also, when quotes are received or identified in published sources, it is often difficult to identify fully what is included in the cost.

Applications, Values & Use

Results of this report will provide EPRI members with information on IOM costs for the various DG technologies. This information will be useful for business planning or for those considering the purchase and installation of a DG system for either commercial use and/or demonstration.

EPRI Perspective

Estimating costs for distributed resources projects can be difficult. Capital equipment costs are generally well known, at least for mature DG technologies. However, IOM costs are frequently underestimated, especially for emerging DG technologies. This report provides a frame of reference for comparing and estimating IOM costs. Cost data in this report are based primarily on firm quotes and field data from actual installations.

IOM costs for emerging technologies (for example, fuel cells and microturbines) are quite high and situation dependent. However, within the next five years these IOM costs may stabilize and fall within ranges that are more consistent with mature DG technologies. For both microturbines and fuel cells, the actual (based on field tests) IOM costs are higher than common quotes or estimates.

Approach

The project team obtained IOM cost data directly from manufacturers and/or distributors of IC engines, combustion turbines, microturbines, and fuel cells. Field installation and maintenance data also were obtained through the EPRI Microturbine Field Demonstration project. These values were supplemented with published information and contacts with other organizations such as the Department of Energy (DOE) and the Department of Defense (DOD). DOD provided data for fuel cell installations. The various installation cost components were categorized for each of the four technologies. Similarly, operation and maintenance cost components were identified.

The team also compared current fuel cell and microturbine IOM costs to similar, but mature, HVAC technologies. For example, small fuel cells targeted at residential applications were compared primarily to residential heat pumps. Larger fuel cells and microturbines for commercial applications were compared to chillers and large heat pumps. This comparison can be useful for determining future IOM cost targets for emerging DG systems.

Keywords

Distributed energy resources
Distributed resources
Distributed generation
Installation
Operation
Maintenance
O&M

ABSTRACT

Distributed generation (DG) technologies have significant installation, operation, and maintenance costs. These costs are often underestimated or overlooked in many discussions related to DG technology costs. Emerging DG technologies such as microturbines and fuel cells tend to have higher IOM costs than their more mature counterparts (IC engines and combustion turbines). Both mature and emerging DG technologies are anticipated to eventually penetrate a significant portion of the residential and commercial building market. This report also compares the IOM costs of DG technologies to residential heat pumps and commercial building chillers.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

Distributed generation (DG) is a broad term that encompasses both mature and emerging onsite power generation technologies with power output as small as 1 kW and as large as 20 MW. This report is intended to provide an overview of the installation, operation, and maintenance (IOM) costs associated with a variety of DG technologies, including:

- Internal combustion (IC) engines
- Combustion turbines
- Microturbines
- Fuel cells

Cost is an important factor with any major purchase, especially with power generation equipment. The two cost components most often considered are capital (equipment) cost and the fuel costs. However, it is important to also consider the cost to install, operate, and maintain the equipment. For example, in some cases the total installed cost of a generator can be twice (or more) the cost of the power generation equipment alone. This report provides a more detailed look at the installation, operation, and maintenance costs of DG technologies. IOM costs for IC engines and combustion turbines are relatively low because of the mature nature of the technologies, while those for microturbines and fuel cells are higher and less predictable because of the new and emerging nature of these devices.

In addition to providing information and data on IOM costs, the Appendices of this report include worksheets and other information useful for calculating costs for specific projects.

Installation Costs

The total "installed cost" of a DG system includes the cost of the power generation equipment plus "installation costs." The term "installed cost" in this report should be considered synonymous to the term "project cost" or "total project cost". The installation costs refer to all costs beyond the power generation equipment that are required for the complete project or installed cost. The installation costs for a DG system include the following components:

- Project engineering
- Permitting
- Site preparation/placement
- Mechanical, including thermal recovery system

- Fuel supply system
- Electrical
- Site commissioning/startup
- Other

Installation costs include both materials/parts and labor. The parts and materials can include items such as concrete for the installation pad to complex heat recovery equipment. The labor costs can also include different components such as concrete work, electrical, and mechanical. Each of these labor rates can be significantly different, and can also vary based on location.

Capital or power generation equipment costs are listed for comparison or completeness in some parts of this report, but power generation equipment costs are not the major focus of this report.

Operation and Maintenance Costs

Operation and maintenance (O&M) costs include all costs to keep the system operating properly, including:

- Maintenance (labor and materials), scheduled and unscheduled
- Consumables (fuel, lubricating oil, coolant, emissions control catalysts and reagents, etc.)

While the cost of fuel is the major component of operation cost, the fuel cost is not covered in detail in this report.

Cost of Electricity

In order for a DG system to be cost competitive with central power generation, the overall cost to produce electricity must be lower that that provided by the power grid. The cost of electricity (COE) is comprised of three primary components:

- Equipment and installation (C&I)
- Operation and maintenance (O&M)
- Fuel (F)

If these three components are known, the cost of electricity can be estimated for a given DG technology. The equipment and installation costs can be amortized over the life of the equipment, and each cost component can be reduced to the cost ($) per kilowatt-hour of electricity produced, or $/kWh. This report covers the installation portion of the C&I cost and the O&M cost. It does not cover the equipment portion of C&I nor the fuel (F) costs.

Objective of the Report

The objectives of this report are to:

- Characterize the installation costs of IC engines, combustion turbines, microturbines, and fuel cells.
- Characterize the operation and maintenance (O&M) costs of IC engines, combustion turbines, microturbines, and fuel cells.
- Compare installation, operation, and maintenance costs for emerging DG technologies to comparable equipment in mature industries (e.g., HVAC, diesel backup gensets, etc.).
- Compare installation, operation, and maintenance costs across technologies.

Organization of the Report

The information presented in this report was obtained from interviews with equipment vendors, EPRI materials, and through secondary research consisting of literature and web-based searches.

The remainder of the report is organized into the following chapters:

- *Chapter 2: Installation Costs* – provides an overview of the acquisition, installation, and indirect costs for IC engines, combustion turbines, microturbines, and fuel cells.
- *Chapter 3: Operation and Maintenance Costs* – provides an overview of the fixed and variable O&M costs for IC engines, combustion turbines, microturbines, and fuel cells.
- *Chapter 4: Comparison of DG and HVAC IOM Costs* – compares the IOM costs of both mature and emerging DG technologies with comparably-sized HVAC technologies.
- *Chapter 5: Summary and Conclusions* – compares the four distributed generation technologies in tabular and graphical format and highlights key installation, operation, and maintenance cost trends.

2 INSTALLATION COSTS

The "installed cost" of a DG system is the power generation equipment cost plus the "installation cost". In general, the power-generation equipment costs for DG technologies are widely known or relatively easy to obtain. The opposite is true for installation cost. Because of the many and varied fees, labor costs, extraneous parts and material costs, the installation can be difficult to quantify. The focus of this chapter is on defining the components of the installation cost and establishing a methodology for estimating a reasonable installation cost for a DG system.

Installation costs for emerging technologies such as microturbines and fuel cells are relatively high and unpredictable compared to more mature DG systems, such as internal combustion engines (ICEs) and combustion turbines (CTs). However, as microturbines and fuel cells approach full-scale commercialization, it is expected that these costs will decline and become more consistent. The installation costs for a DG system can be categorized as follows:

- Project engineering – includes additional engineering of the system outside of the packaged unit. In some cases the heat recovery system or the gas compressor are separate units and require additional design for implementation. Additional project engineering costs may include planning, project management, site design, fuel system design, thermal system design, interconnection design, and customer load profiling.
- Permitting – includes all fees associated with permitting the unit for installation (e.g., basic site installation, mechanical, electrical, emissions, noise).
- Site preparation/placement – includes any concrete work, fencing, noise reduction enclosures or structures, equipment rental, labor, and additional site preparation.
- Mechanical, including thermal recovery system – includes additional system components and the connection of the thermal recovery system to both the power generation unit and the end use of the thermal energy.
- Fuel supply system – includes components such as piping, regulators, and meters, and the labor to installs these components between the fuel source and the power generation module.
- Electrical – includes components such as meters, wiring, controls, and system connections.
- Site commissioning/startup – includes any additional costs associate with the startup of the system, e.g., emissions testing and verification.
- Other – may include emissions control systems and other exhaust aftertreatment as well as shipping or additional components not included in one of the above categories.

Each of the technologies will have some variation to the installation cost breakdown in each of these categories as described in this chapter. **Appendix A** includes an example installation cost calculation and a blank template to assist in calculating specific installation costs for a specific application.

Installation costs, O&M costs, and even the power rating of power generation equipment depends upon its anticipated application: continuous, prime, peaking, or standby. The commonly used definitions of these terms are included in **Table 2-1.** For comparison, there are 8760 hours in a standard year and 8784 hours in a leap year. As indicated in the table, standby power-generation equipment is normally operated well below its rated capacity to assure that the equipment is never overloaded and to enhance its reliability.

Table 2-1
Generation System Duty Cycle Definitions

	Operation (hr/yr)	% of Full Load Operation
Continuous Duty	> 8,000	100 %
Prime Power	4,000-8,000	100 %
Peaking	1,500-4,000	100 %
Standby	< 200	60 %

Internal Combustion Engines

The cost to install an IC engine is relatively low when compared with other DG technologies, primarily because they are quite common and the installation requirements are well known. This section covers a brief review of IC engine equipment costs, followed by a more detailed look at the installation cost components.

The main factors affecting internal combustion engine (ICE) equipment costs are:

- Engine size
- Speed
- Type (compression ignition or spark ignition)
- Production volume
- Manner of production (automated assembly line versus built-to-order with more labor-intensive manufacturing, cast iron block versus rolled steel block, etc.)

In contrast to other types of power generation equipment, IC engines exhibit negative economies of scale ($/kW cost increases with size). This is a consequence of the reduction in crankshaft speed (causing a decrease in power output per unit of cylinder displacement) and increased engine mass. Heat recovery equipment adds approximately 20 to 30% to the system installed cost.

Generally, a company's most expensive engines are large, low-speed, state-of-the-art engines that are also its most efficient and lowest emission engines. Its lower cost models tend to be its older, smaller, higher-speed, reliable, rugged, and more popular engines. The lower cost models are often rich burn (while the most expensive gas engines are lean-burn), have lower BMEP, lower compression ratio, and less advanced engine control systems.

IC engines lend themselves well to reconditioning. A number of companies have been in the engine rebuilding business for years. Rebuilt engines have proven their reliability in many industries and applications. Prices of used or reconditioned equipment are typically about half that of comparable new equipment.

Gas engine generator sets (as illustrated in **Figure 2-1**) generally include the base, engine, and generator (but with no fan, radiator, installation, or shipping). **Table 2-2** lists the acquisition and installation costs (per kW_e) for some typical applications of gas and diesel engine generator sets and power modules. A diesel engine generator set generally includes the base, engine, generator, radiator, and fan (no installation or shipping). In contrast, the term 'power module' implies that the power generation equipment is delivered inside a 40-ft container (such as is shown in **Figure 2-2**). The power module package includes the engine, generator, cooling, exhaust, lube-oil makeup, positive ventilation, digital regulator, continuous pre-lube, circuit breaker, engine/generator controls, remote start and stop, auto switchgear, utility switchgear, load sharing, fuel tank (diesel only), starters, and batteries. The typical set-up time for a power module is only 1 to 3 hours, since it mostly involves connecting control cables, fuel lines, and power cables. The installed cost of a power module is generally less than the corresponding gen-set; e.g., when the same engine and generator included in ICE4 (a diesel gen-set for standby power) is incorporated into a diesel power module for standby power, the total project cost drops from about \$342 to \$261/kW_e.

Figure 2-1
Generator Set Installation (2.0 MW_e each unit)

Table 2-2
Selected ICE Equipment Package and Installation Costs per kW_e

Engine Type	Gas Gen-set for Continuous Duty	Gas Gen-set for Prime Power	Gas Power Module for Peaking	Diesel Gen-set for Standby Power	Diesel Gen-set for Standby Power
Engine Reference[1]	ICE1	ICE2	ICE3	ICE4	ICE5
Fuel	Natural Gas	Natural Gas	Natural Gas	Diesel	Diesel
Application	Continuous Duty	Prime Power	Peaking	Standby	Standby
Rating (kW_e)	1,300	1,400	1,250	2,000	2,000
Major / Minor Cost Component	**Cost ($/$kW_e$)**	**Cost ($/$kW_e$)**	**Cost ($/$kW_e$)**	**Cost ($/$kW_e$)**	**Cost ($/$kW_e$)**
Engine / Generator / Base / Safety System	286.78	269.14		183.01	158.63
Project Engineering					15.00 (not included)
Permitting	Not included	Not included	Not included	Not included	Not included
Site Preparation / Placement / Enclosures	Included	Included	Included	Included	38.09 (excl. site preparation & placement)
Fuel Supply System	1.21 (Installation included below)	1.13 (Installation included below)	Included	0.35 (Installation included below)	19.34
Electrical	20.35 (Installation included below)	18.89 (Installation included below)	Included	16.06 (Installation included below)	36.20 (installation of switchgear and controls not included)
Mechanical (cooling and exhaust connections)	Included	Included	Included	Included	$6.50
Site Commissioning / Startup	Included	Included	Included	Included	$6.00
Other (Equipment and Installation of SCR System)					106.03 (not included)
Estimated Installation Costs	279.25	270.02		158.91	106.13
Total Project Costs	566.03	539.16	527.83	341.91	264.75

[1] See Appendix E for a cross reference of the specific engine model.

Figure 2-2
Diesel Power Module at a Utility Site (2.0 MW_e)

Regarding the ICE1 gas engine generator set for continuous duty, the engine generator set package includes:

- 480V Generator
- Fuel system with fuel filter, regulator, but no local piping
- Switchgear (480V Basic, Load Sharing, Circuit Breaker, Auto Parallel, Self Protecting, Meters, Customer Interface)
- Cooling System (Remote Radiators)

Similarly, the ICE2 gas engine generator set for prime power includes:

- 480V Generator
- Fuel system with fuel filter, regulator, but no local piping
- Switchgear (480V Basic, Load Sharing, Circuit Breaker, Auto Parallel, Self Protecting, Meters, Customer Interface)
- Cooling System (Cooling Towers)

The ICE3 gas power module package (for peaking power) includes:

- 480V Generator
- Complete Module (Cooling System, Exhaust System, Lube Oil Makeup, Positive Ventilation, Digital Regulator, Continuous Pre-lube, Circuit Breaker, Engine/Generator Controls, Remote Start, Remote Stop, Auto Switchgear, Utility Switchgear, Load Sharing, 40 ft container, Starters, Batteries)

The typical set-up time for the ICE3 power module is 1 to 3 hours. Not included in this set-up time is the time required to prepare the site (to clear a place to park the power module trailer), to install the fuel system (a pipe to deliver natural gas), to install the cable from the site to the remote control system, and to install power cables (minimal if the power module is properly located).

Regarding the ICE4 diesel engine generator set for standby power, the engine generator set package includes:

- 480V Generator
- Fuel system with fuel filter but no local piping
- Switchgear (480V Basic, Load Sharing, Circuit Breaker, Auto Parallel, Self Protecting, Meters, Customer Interface)
- Cooling System (Mounted Radiator)

The following apply to the ICE5 diesel generator set for backup power:

- Mechanical installation includes mounting generator set on springs and the enclosure connections for fuel and exhaust
- Electrical installation includes low voltage power only for lights, chargers, etc., in the enclosure, with main power and controls tied together
- Startup includes basic startup and testing of system to utility load for 5 days
- Extended testing and commissioning cost would be extra depending upon complexity of procedure required
- The components of installation costs included are mechanical ($13,000 or $6.50/kW), electrical, controls, and low-voltage service ($1,500 or $0.75/kW), site commissioning/start-up ($12,000 or $6.00/kW)
- Selective Catalytic Reduction (SCR) system cost (not included in the total project cost in **Table 2-2** was estimated to be $147,000 ($73.50/kW) plus $65,000 ($32.50/kW) for SCR system installation
- Project engineering is not included in the total project cost in **Table 2-2**, but its cost was estimated to be $30,000 ($15.00/kW)

Figure 2-3 illustrates how the total installed cost ($/kW) and power generation equipment cost ($/kW) varies with fuel type and by application. Diesel generator sets are less expensive than natural gas generator sets, and less expensive to install. Installation costs are comparable to or slightly less than equipment costs. Generator sets used for standby power are usually oversized to assure adequate capacity in an emergency, but they are also rated at higher power due to the shorter operating hours. A generator set packaged in a power module is less effort to install and therefore less cost to install.

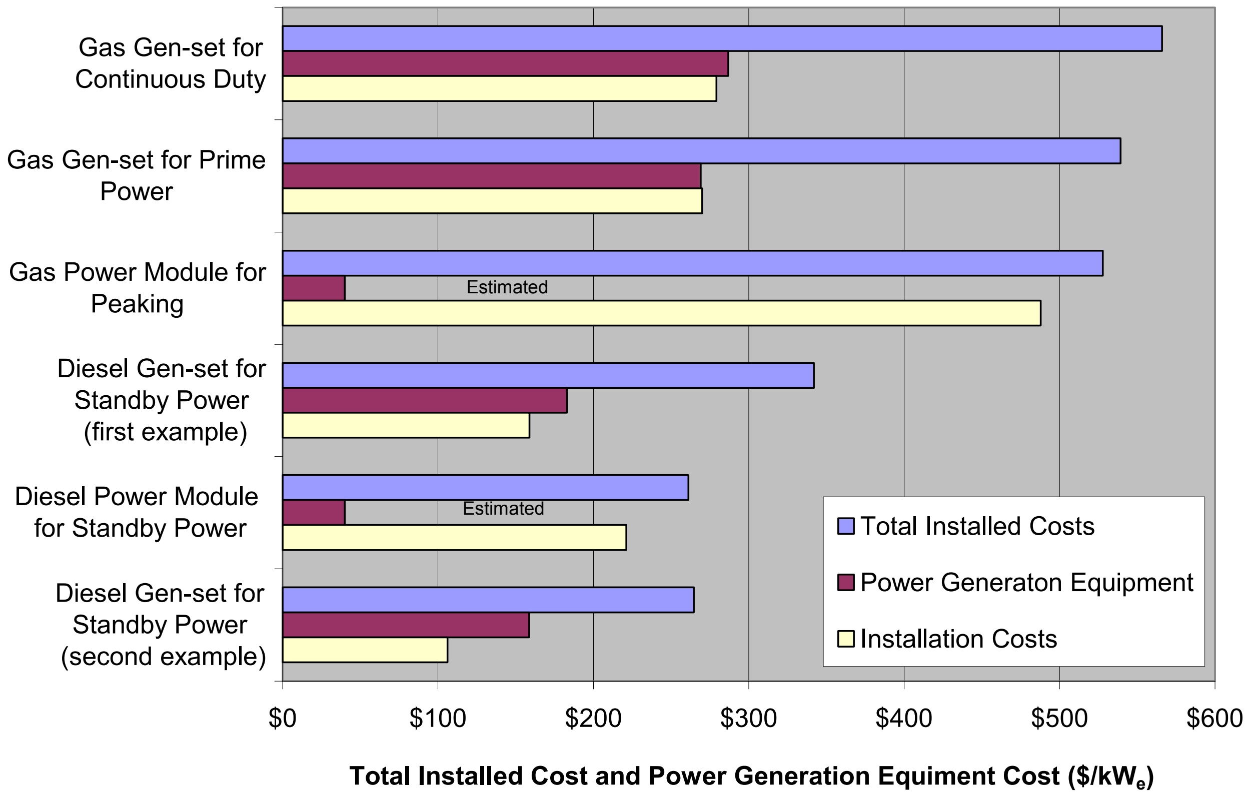

Figure 2-3
Typical ICE Total Installed Costs and Engine Power Generation Equipment Costs ($/kW$_e$)

Figure 2-4 shows a typical distribution of installation costs for ICE power generation equipment with an emissions control system but with no cogeneration system. The cost shown corresponds to a diesel generator set installed for standby power (ICE5) with an SCR emissions control system (SCR is suitable for use only on engines using considerable excess air). The cost of the emissions control system combines the equipment capital and installation costs. Other than the power generation equipment cost of $158.63 (not shown), the major cost component is the emissions control system. Because of the high cost, emissions control systems are rarely installed on backup power systems.

ICE power-generation equipment costs per kW generally increase with size, so that the cost per kW of a 10-MW system is about twice the cost per kW of a 2-MW system. ICE installation costs are different. The installation cost per kW of a 10-MW system is about the same (or slightly less) than the cost per kW of a 2-MW system.

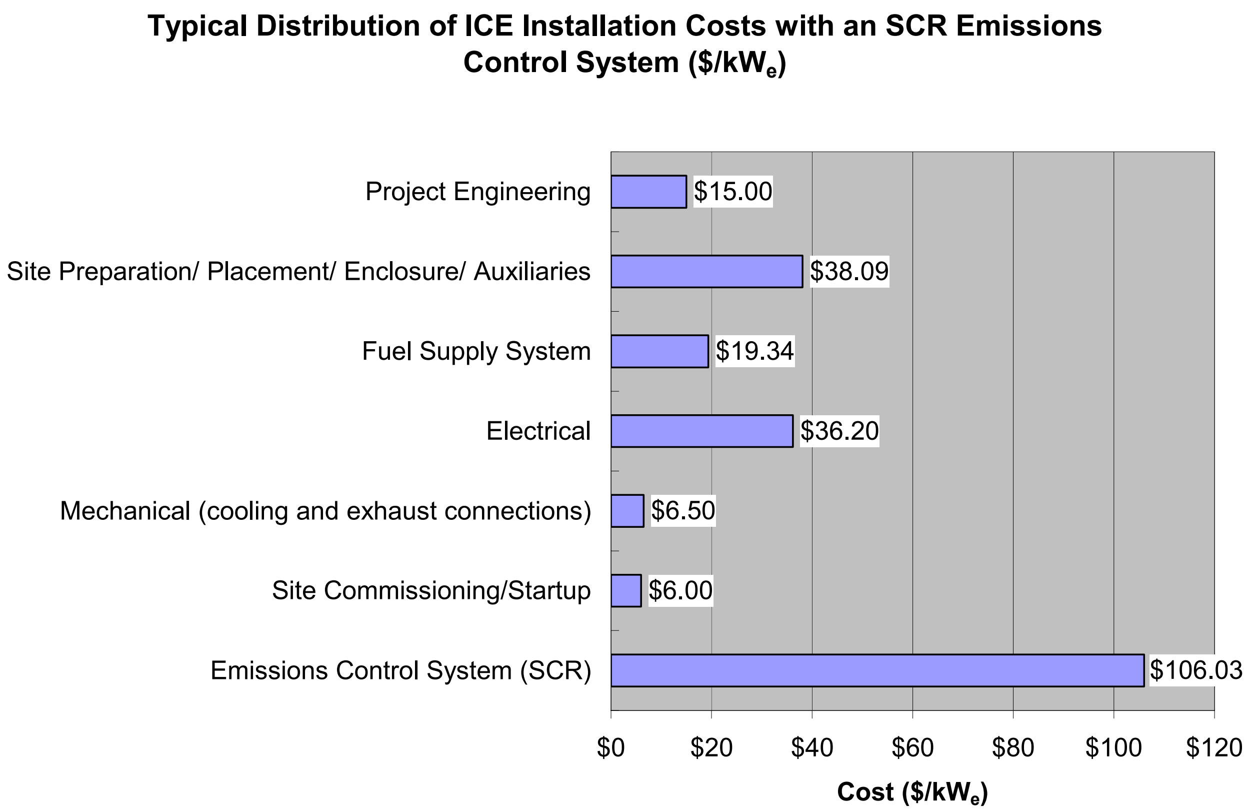

Figure 2-4
Distribution of Diesel Backup ICE Installation Costs with an SCR Emissions Control System ($/kWe)

In summary, a representative number for the total project cost of a 2-MW ICE power generation system without an SCR system is $400/kW, where the cost of the power generation equipment is around $200/kW and the installation costs is around $200/kW. The installation of an SCR system adds another $100/kW.

Combustion Turbines

The main factors affecting combustion turbine (CT) equipment costs are:

- Size (output power rating)
- Type (aeroderivative or industrial)
- Added features (e.g., heat-recovery steam generation (HRSG), steam injection, combined cycle, cogeneration)

CTs exhibit the economics of scale ($/kW cost decreases with size). Aeroderivative CTs are generally more costly than heavy frame industrial CTs, but aeroderivative CTs are more fuel-efficient in the simple-cycle mode of operation. Heat-recovery steam generators (HRSGs) in the

CT exhaust flow add to the complexity and cost of the system, and slightly reduce the performance of the CT itself due to added pressure drop in the exhaust flow. The steam generated by the HRSG can be used in several ways:

- Steam injected into the combustor between the compressor and the turbine will boost the output power of the CT
- Steam supplied to a steam turbine increases the system output power (the steam turbine can be on the same shaft as the gas turbine or can power a separate generator)
- Cogeneration (also known as combined heat and power, or CHP)

The total installed cost (or total project cost, TPC) is composed of the cost of the power generation unit (equipment-only) and the installation costs. The installation costs of larger CT systems are typically 60 to 80% of the cost of the power generation unit. Because DR-size CT systems are usually packaged and modularized, the power generation units are the dominant part of total installed cost. The power generation unit for a basic combustion turbine generator set package includes the combustion turbine (CT), generator, and controls. The installation costs include:

- Project engineering (engineering and management)
- Permitting (permits and licensing)
- Site work (site preparation/placement/enclosures)
- Fuel supply system
- Electrical (transformers and switchgear)
- Mechanical (balance of plant equipment not included with power generation unit, installation of HRSG, cooling, and exhaust connections)
- Site commissioning and startup
- Other (freight, licensing and insurance, financial carrying costs, emissions control systems)

Table 2-3 gives the typical range of installation costs and power generation unit costs for three sizes of basic generation packages. This table also illustrates the economies of scale of CT systems. Additional features such as fuel gas compression, heat recovery, water treatment, and emissions control are not included in the costs in **Table 2-3**.

Table 2-3
CT Installation Costs Depend on Size (Basic Generation Package)[2]

Turbine Size	Installation Cost Range ($/kW)	Power Generation Equipment Cost Range ($/kW)
1 MW	450-1000	400-600
5 MW	250-600	360-430
25 MW	200-500	300-370

Source: Manufacturers

Figure 2-5 shows a typical example of the distribution of installed costs for combustion turbines (corresponds to the data in the column labeled CT4 in **Table 2-4**, except that the HRSG equipment is not included, which reduced the 'Other' category by $150/kW). The total installed costs are at least 1.6 times higher than the power-generation equipment costs. However, for complex cogeneration (CHP) facilities and other installations that require HRSG, the total installed cost is often 2-3 times higher than the power-generation equipment costs.

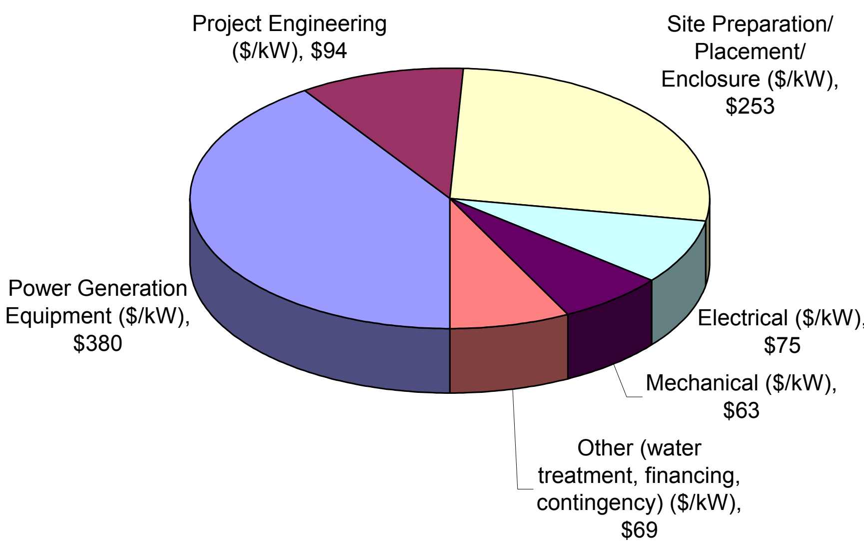

Figure 2-5
Typical Distribution of Installed Costs for Combustion Turbine Systems

[2] Does not include HRSG or SCR.

Table 2-4 lists the acquisition and installation costs (per kW_e) for some typical CT systems.

Table 2-4
CT Installation Costs ($\$/kW_e$) as a Function of Power Rating (kW) for Natural Gas-Fired, Continuous Duty Applications

CT Reference	CT1	CT2	CT3	CT4	CT5	CT6	CT7
Rating (MW_e)	1.2	1.9	3.8	5	5.1	6.3	23.3
Cost Component	Cost ($\$/kW_e$)	Cost ($\$/kW_e$)	Cost ($\$/kW_e$)	Cost ($\$/kW_e$)	Cost ($\$/kW_e$)	Cost ($\$/kW_e$)	Cost ($\$/kW_e$)
Engine / Gen./ Base / Safety System	563	197	440	380	360	430	365
Project Engineering	157	74	Included	94	Included	Included	69
Permitting	Included	Included	Included	Included	Included	Included	Included
Site Preparation / Placement / Enclosures	410[3]	203	Included	253 [3]	Included	Included	181 [3]
Fuel Supply System	Included	Included	Included	Included	Included	Included	Included
Electrical	125	28	Included	75	Included	Included	42
Mechanical (cooling and exhaust connections)	121	144	Included	63	Included	Included	49
Site Commissioning / Startup	Included	Included	Included	Included	Included	Included	Included
Other	413[4]	100[5]	Included	219 [4]	Included	Included	138 [4]
Estimated Installation Costs	1226	549	340[6]	705	240 [6]	520-870	480
Total Installed Costs	1788	746	780	1085	600	950-1300	845

[3] Includes all installation labor and miscellaneous materials
[4] Includes equipment costs for HRSG, water treatment system, project financing costs, and contingency
[5] Estimate for permitting, mechanical and electrical installation labor, site commissioning and startup
[6] Includes HRSG with bypass, simple electrical switchgear, and simple structure

In summary, the total project cost for a basic 5-MW CT power generation system is $700/kW (ballpark number), and, of that, the power generation equipment costs run about $400/kW and the installation costs are at least $300/kW. The installation of heat recovery equipment adds at least $150/kW and an SCR system adds another $80/kW.

Microturbines

Microturbines are currently considered early commercial systems. Installers have limited experience to date; hence, current installation costs are high relative to what they might be if a large market develops.

In **Table 2-5**, the labor hours for individual components of installing a microturbine are based on actual site demonstrations[7]. The estimates of labor hours are quite high since additional design and engineering is associated with a new installation. These additional costs are not typical of a normal mature technology installation. Labor hours may increase for a more difficult installation or decrease in a simplified situation. Additional materials are typically required and not included in the labor cost estimate.

Table 2-5
Microturbine Installation Labor Hours and Cost for an Example Demonstration Installation

Installation Task	Labor Hours (estimate)	Labor Cost (at $50/hour)
Site Preparation / Placement	150	$7,500
Fuel Supply System	200	$10,000
Electrical	250	$12,500
Thermal Recovery System	120	$6,000
Site Commissioning / Startup	25	$1,250
Other	80	$4,000
Total	**825**	**$41,250**

1. Data in this table are based on three 30-kW demonstration installations in the EPRI MTG Field Test Program (1006394)
2. Labor rates are assumed to $50/hour, however, will differ based on location and by the type of work (e.g., mechanical work may have a different rate than electrical)
3. Hours for the fuel supply system and electric are high due to added design and interconnection planning for a demonstration

[7] Based on data from EPRI Report *MTG Field Test Program: Interim Results*, 1006394, December 2001.

Three microturbine demonstration installations from EPRI's Microturbine Field Test Program are highlighted in this section for comparison of installation costs. Some of the preliminary performance and cost results from over 40 microturbine installations are outlined in the *MTG Field Test Program: Interim Results*, December 2001, Report Number 1006394. The three systems highlighted for this installation cost discussion are 30 kW units and have the configuration characteristics in **Table 2-6**.

Table 2-6
Microturbine Demonstration System Setup

	Model 1	Model 2	Model 3
Fuel Type	Natural Gas	Natural Gas	Diesel Oil
Grid Connected		X	X
Grid Independent	X	X	X
Heat Recovery	X		
Comments		Utility provided some cost sharing of in-house labor and re-usable materials for this installation	

Table 2-7 compares the component costs of installation for each of these three microturbine systems. Model 2 costs are lower due to some cost-shared labor and materials not reported. The addition of heat recovery equipment for CHP applications (Model 1) adds a significant cost to the installation.

Table 2-7[8]
Cost Components and the Impact on Total Installation Cost ($/kW)

Cost Component	Model 1 Natural Gas w/ CHP		Model 2 Natural Gas		Model 3 Diesel Oil	
Microturbine power generation unit only	***1,000***		***1,000***		***1,000***	
	Labor[9]	**Materials**	**Labor**	**Materials**	**Labor**	**Materials**
Fuel system	567	105	34	65	120	90
Electrical	366	145	172	150	427	195
Remaining installation materials and labor	40	829	156	376	387	725
Heat recovery	214	408	---	---	---	---
Sub-total	*1,187*	*1,487*	*362*	*590*	*934*	*1,010*
Total installation cost	***2,674***		***952***		***1,944***	
Project Total ($/kW)	**3,674**		**1,952**		**2,944**	

[8] This table includes data for three 30-kW microturbines from the EPRI MTG field Test Program. The MTGs were selected because the cost component data were reported in detail. They are not necessarily "typical" installations.
[9] Based on a labor rate of $50 per hour

Figure 2-6 illustrates the variation within the different installation cost components for the three 30 kW microturbine systems. Model 1 includes a thermal recovery unit and has the highest overall installation cost. Model 2 has the lowest installation cost, primarily because the host donated a significant part of the installation labor and some materials.

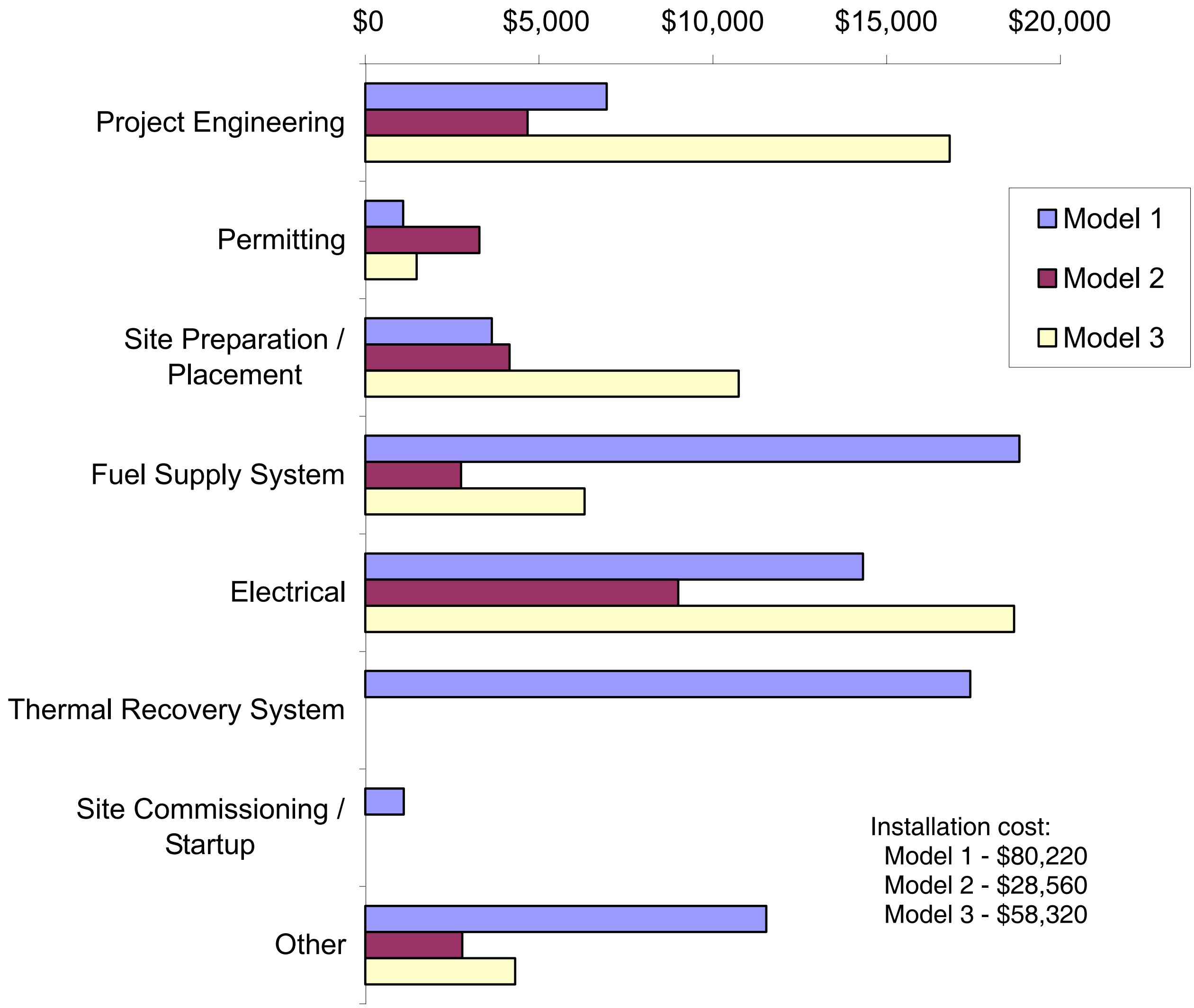

Figure 2-6
Microturbine Demonstration Installation Cost Comparison

The average installation cost of these three microturbines is $55,700, or $1856/kW.

The power output of the microturbine has minimal effect on the overall installation cost; therefore the cost per kilowatt will be lower for larger systems. Site-specific influences, such as those listed below, will affect the installation cost regardless of the early commercial status of microturbines:

- Longer distance from the point of electrical interconnection or more difficult interconnection scenario (increasing materials costs and taking longer to install)
- Long or difficult fuel interconnection (increasing materials and labor costs)
- Indoor installations increase the cost (additional noise and emission regulations, as well as the additional physical barriers indoors)
- Fuel type will affect the installed cost (liquid fuel requires storage)

Manufacturers are predicting that the installation cost of microturbines as a mature technology will be approximately 20-30% of the equipment cost. This contrasts with demonstration installations that are anywhere from 100 to 250% of the capital equipment costs.

Figure 2-7 illustrates the projected decrease in installation costs, regardless of system power output, for a standard outdoor installation of a natural gas microturbine with CHP. As part of the EPRI MTG Field Test Program, demonstration sites were required to submit actual installation costs as well as projected costs for a commercial installation of the same product. The *Projected Installation Costs* in **Figure 2-7** are based on the average reduction in cost projected by the utility hosts responsible for the demonstration sites. These commercial projections still represent approximately 50-60% of the capital equipment costs, not the 20-30% that manufacturers predict.

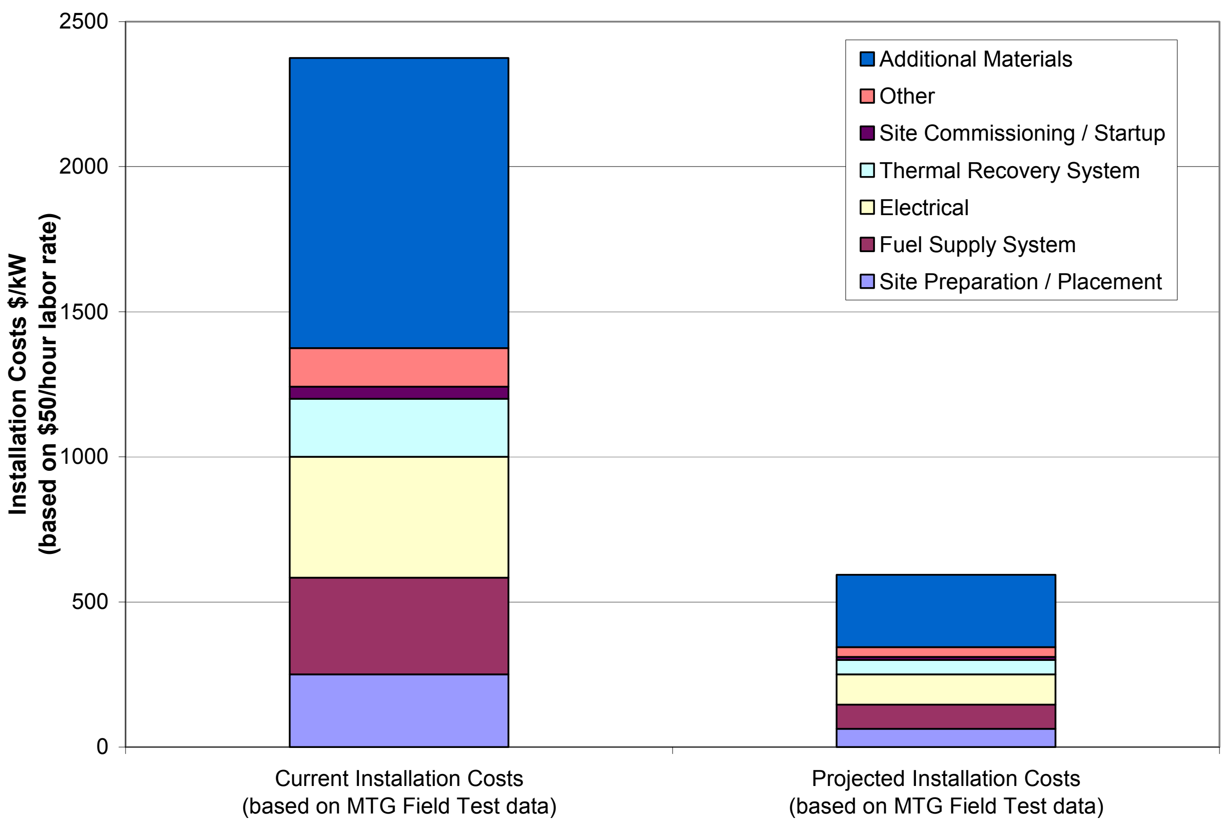

Figure 2-7
Current and Projected Installation Labor Costs for a 30-kW Microturbine

One reason for high costs in the early installations is that auxiliary components are not packaged with the microturbine unit as a complete system. Auxiliary components suitable for packaging include the gas compressor, heat recovery, and associated piping and wiring, and standardized interconnection hardware.

For natural gas or propane microturbine installations, the average installation cost projected by demonstration sites in the MTG Field Test program for the 30 kW units is $16,500 or $550/kW. In summary, current microturbine installation costs can range from $1,000 -$2,500/kW. Microturbines have an approximate installation cost of $2,000/kW (roughly 200% of the capital equipment cost).

Fuel Cells

There are four predominant types of fuel cells, each in various stages of development and commercialization, and each named for the type of electrolyte and materials employed in its construction:

- Molten Carbonate Fuel Cell (MCFC)
- Phosphoric Acid Fuel Cell (PAFC)
- Polymer Electrolyte Membrane Fuel Cell (PEMFC)
- Solid Oxide Fuel Cell (SOFC)

With the exception of PAFC technology, fuel cells remain in the testing and demonstration phase; hence, there is limited data on the costs required to procure and install a fuel cell system.[10] Equipment and installation costs are commonly unique to each individual installation. Fuel cell developers frequently adjust the price between each field demonstration based on a number of factors, including:

- *Additional system options requested* – Certain applications may require high-grade heat recovery, an absorption chiller, installation of a water storage tank, water purification systems, etc. Each of these items increases the cost of the system.
- *Geographical location of the demonstration* – The performance of a fuel cell system may be significantly affected by geography and climate (e.g., temperature, altitude, earthquakes, snow, rain, sunshine, etc.). The developer may need to incorporate upgrades into the design of the system in order to meet the climatic requirements. Geographical location may also impact the costs of delivery, installation, support services, and maintenance.

[10] The UTC Fuel Cells PC25 product, based on PAFC technology, is considered the only “commercially available” fuel cell system to date.

- *Overall size of the commitment* – Fuel cell developers generally offer a lower sale price to strategic partners that have committed to long-term support in technology development, manufacturing, and/or marketing. Also, a commitment to demonstrate several fuel cell systems usually equates to a much lower per unit price than an order for a single fuel cell system.
- *Experience* – Based on field experience gained thus far, some fuel cell developers have been able to lower their prices over the past few years. Others have increased their prices due to losses incurred during early demonstrations.

The equipment and installation costs in this section are based on data provided by specific manufacturers and their demonstration partners. As shown in **Table 2-8**, the current (2002) equipment costs for a pre-commercial fuel cell system can be as high as $30,000[11] per kilowatt. Meanwhile, many developers are projecting future equipment costs to be as low as $300 per kilowatt[12].

Table 2-8
Fuel Cell Systems Equipment Cost ($/kW)

Technology	Current Equipment Cost ($/kW)[13]	Projected Equipment Cost ($/kW)[14]
MCFC	4,000-5,000	900 -1,500
PAFC	3,000-4,500	---
PEMFC	5,000-30,000	300-1,000
SOFC	4,000-20,000	400-1,500

A recent National Renewable Energy Laboratory report[15] breaks down fuel cell system equipment into five major subsystems:

- *Stack subsystem* – fuel cell stacks, feed gas manifolds, and power take-offs
- *Fuel processing subsystem* – fuel controls, reformer, steam generators, shift reactors, sulfur absorbent beds, and other fuel-intake components
- *Power and electronic subsystem* – solid-state boost regulator, inverters, grid interconnect switching, load management and distribution hardware, and controllers
- *Thermal management subsystem* – stack cooling system, heat recovery, and condensing heat exchangers
- *Ancillary subsystems* – process air supply blowers, water treatment system, safety controls and monitoring, cabinet ventilation fans, and other miscellaneous items

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[11] Based on the current price for a one-year lease of the Nuvera 5-kW Avanti PEMFC system.

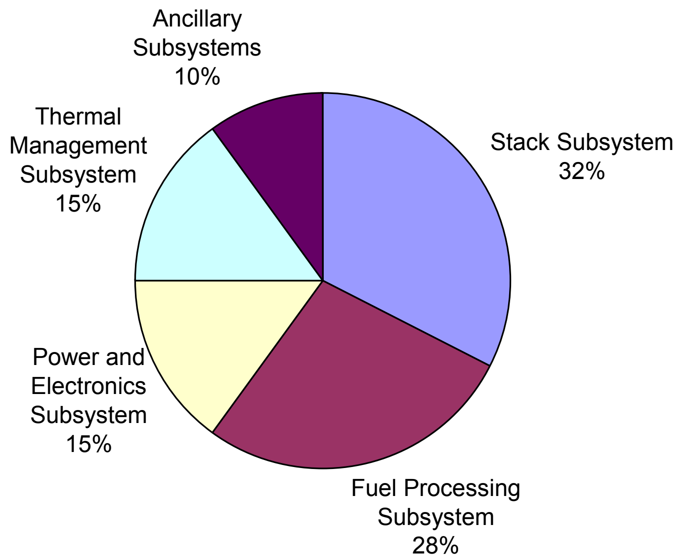
[12] This common cost projection assumes a large and successful automotive market for PEMFCs.

[13] Based on data provided by a variety of fuel cell developers and rounded to the nearest $500. More specific equipment and installation cost data is provided later in this chapter.

[14] Based on projections provided by a variety of fuel cell developers. The future projections are made in a general sense and are not associated with a particular year or production level. The authors believe these projections to be very optimistic and depend on high-volume production.

[15] "Gas Fired Distributed Generation Technology Characterizations, Fuel Cell Systems," April 2002 Draft

The magnitude of these costs to the overall equipment cost will vary by system type and design. **Figure 2-8** illustrates a general relationship of the different equipment cost components.

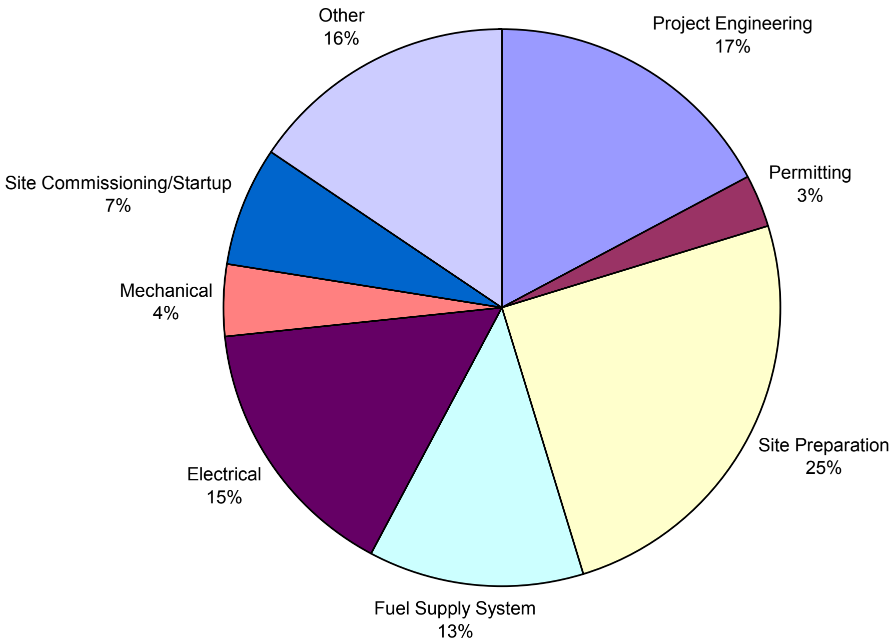


Source: "Gas Fired Distributed Generation Technology Characterizations, Fuel Cell Systems," April 2002 Draft, National Renewable Energy Laboratory

Figure 2-8
Fuel Cell Equipment Cost Breakdown by Subsystem (Total Cost is $4000/kW)

As previously mentioned, relatively few fuel cell systems have been installed to date, and installation costs are highly site-dependent. **Figure 2-9** shows an estimated breakdown of installation costs for an "electric-only" application based on data collected by the DOE.[16] Because heat recovery is not included, the "mechanical cost" category is relatively low as the system requires less piping and hardware installation. The "other" category is high (at 16%) in order to account for contingencies required during the installation.

[16] "Gas Fired Distributed Generation Technology Characterizations, Fuel Cell Systems," April 2002 Draft



Source: "Gas Fired Distributed Generation Technology Characterizations, Fuel Cell Systems," April 2002 Draft, National Renewable Energy Laboratory

Figure 2-9
Representative Fuel Cell System Installation Cost Breakdown (Total Cost is $650/kW)

In general, the installation costs of fuel cell systems should be relatively consistent with other engine-based equipment that requires a fuel supply connection, as well as electrical connections. However, near-term installation costs for fuel cells vary widely depending on the site. As a general rule of thumb, installation costs for distributed generation systems may add 50-100% (of the equipment cost) to the total project cost. But because current fuel cell equipment costs are so high, this proportion may be somewhat less. While there are very little data available related to PEMFC and SOFC installations, one may look to PAFC and MCFC demonstrations for installation cost data.

PAFC Demonstrations

The U.S. Department of Defense (DOD) conducted a demonstration program with PAFC systems throughout the 1990s. Thirty PC25 fuel cell systems manufactured by UTC Fuel Cells (formerly ONSI and International Fuel Cells) were installed at DOD bases in seventeen states between 1994 and 1997. The objectives of the demonstration program were to:

- Demonstrate fuel cell capabilities in real world situations
- Stimulate growth and economies of scale in the fuel cell industry
- Determine the role of fuel cells in the DOD's long term energy strategy

Table 2-9 provides actual equipment and installation cost data for the PC25 systems, which are rated at 200 kilowatts of electric output. The way the demonstration program was structured, the DOD was charged the same base amount for each system installed regardless of the installation date, location, or PC25 version[17]. The total installed cost, including a one-year maintenance contract, for the standard PC25 package was just under $4,000 per kilowatt. Installation accounted for about 20% of that cost, or $800 per kilowatt. This installation cost is also representative of the equipment cost plus 25% (i.e., $3,182 + 25%), which is much lower than the rule of thumb defined in the previous section. It is worth noting that just the equipment cost of a UTC Fuel Cells PC25C unit today varies between $3,000 and $4,500 per kilowatt (Table 2-8).

Table 2-9
DOD Fuel Cell Program – PC25 Standard Package Costs

Item	Cost ($)	Cost ($/kW)
Power Plant Equipment Cost	$636,525	$3,182.63
Installation Cost (including 1-year maintenance package)	$160,727	$803.63
Total Installed Cost	**$797,252**	**$3,986.26**

Source: U.S. Department of Defense, Army Corps of Engineers, Engineer Research and Development Center (ERDC), Construction Engineering Research Laboratory (CERL)

Optional add-ons increased the project costs of each PC25 installation based on the specific requirements at each military site. **Table 2-10** lists the DOD price for some common options. Therefore, the $800/kW is at the low end of the installation cost range. Selection of several of the optional items listed in **Table 2-10** resulted in higher installation costs. For example, addition of a transformer alone added about $165 per kilowatt to the installation cost. It is also important to note that location can make an impact on the installation costs. The shipment and installation of a PC25 system in Alaska added more than $180 per kilowatt.

The costs in **Table 2-10** represent the equipment and installation costs paid by the DOD for each PC25 system. The DOD was able to negotiate a flat rate for system options and installation in order to simplify budgeting for each of the military bases that installed a PC25 unit.

[17] Throughout the course of the demonstration program, UTC Fuel Cells delivered three different versions of the PC25 fuel cell system: PC25A, PC25B, and PC25C. The PC25C is the most recent version, which is commercially available today.

Table 2-10
DOD Fuel Cell Program – PC25 Optional & Add-on Costs

Item	Cost ($)	Cost ($/kW)
Additional 2-Year Maintenance Package	$52,936	$265
Additional Maintenance (per month)	$2,263	$11
Grid Independent	$33,675	$168
Transformer	$32,968	$165
High-Grade Heat	$12,768	$64
Second Low Grade Heat	$24,675	$123
Second Thermal Loop	$25,197	$126
Storage Tank	$21,350 + $15.6547 per additional gallon over 1,000 gallons	$107+
Dual Fuel Option	$15,000	$75
20-ton Absorption Chiller	$70,000	$350
30-ton Absorption Chiller	$100,000	$500
Alaska Differential	$36,203	$181

Source: U.S. Department of Defense, Army Corps of Engineers, Engineer Research and Development Center (ERDC), Construction Engineering Research Laboratory (CERL)

Table 2-11 lists site and cost information for eighteen of the thirty PC25 demonstrations. The total installed cost for each of these sites includes 56 months of maintenance service and support provided by UTC Fuel Cells (i.e., one year included in standard package plus two-year option plus twenty additional months). It is shown that the average installed cost for these eighteen military sites between 1994 and 1997 was $931,800, or $4,659 per kilowatt. This means that on average each site selected about $675/kW in options. Assuming that all of these options directly impacted installation (as opposed to equipment cost), then the average installation cost for each military site was approximately $1,479/kW (i.e., $804/kW for standard installation package + $675/kW in options). In this case, installation represents about 32% of the total installed cost. It is also representative of the equipment cost plus 46% (i.e., $3,183 + 46%), which is consistent with the rule of thumb defined in the previous section for calculating installation costs for distributed generation.

Table 2-11
DOD Fuel Cell Program –PC25 Total Installed Costs

Site	Location	Model	Start-up	Status	Installed Cost[18]
Army					
Fort Bliss	El Paso, TX	PC25C	Sept-97	Decommissioned Jun-02	$928,416
Fort Huachuca	Sierra Vista, AZ	PC25C	Jul-97	Operational	$933,413
Fort Richardson	Anchorage, AK	PC25C	Apr-97	Off-line Apr-01	$1,003,291
Pine Bluff Arsenal	White Hall, AR	PC25B	Oct-97	Decommissioned Jun-01	$895,448
Watervliet Arsenal	Watervliet, NY	PC25B	Oct-97	Off-line Jul-02	$895,448
Airforce					
911th Airlift Wing	Pittsburgh, PA	PC25C	Feb-97	Decommissioned Oct-01	$969,856
Barksdale AFB	Bossier City, LA	PC25C	Jul-97	Operational	$895,448
Davis-Monthan AFB	Tucson, AZ	PC25C	Dec-97	Off-line Apr-02	$1,041,184
Edwards AFB	Palmdale, CA	PC25C	Jul-97	Off-line Jul-02	$908,216
Laughlin AFB	Del Rio, TX	PC25C	Sept-97	Operational	$920,123
Little Rock AFB	Jacksonville, AR	PC25C	Oct-97	Shut down Dec-00	$895,448
Westover ARB	Chicopee, MA	PC25C	Sept-97	Off-line Jul-02	$966,381
Navy/Marines					
CBC Port Hueneme	Port Hueneme, CA	PC25B	Aug-97	Operational	$953,091
NAS Fallon	Fallon, NV	PC25C	Mar-97	Off-line Mar-02	$1,007,827
Naval Hospital, NAS Jacksonville	Jacksonville, FL	PC25C	Apr-97	Off-line Apr-02	$920,123
Naval Oceanographic Office	Stennis Space Center, MS	PC25B	Sept-97	Operational	$895,448
Subase New London	Groton, CT	PC25C	Oct-97	Operational	$908,544
National Def. Center for Envir. Excellence	Johnstown, PA	PC25C	Aug-97	Operational	$834,695
				Average Installed Cost	**$931,800 ($4,655/kW)**

Source: U.S. Department of Defense, Army Corps of Engineers, Engineer Research and Development Center (ERDC), Construction Engineering Research Laboratory (CERL)

[18] Includes 56 months of maintenance provided by UTC Fuel Cells.

The following cost data from recent PC25C purchases and installations provides a means of comparing the DOD PC25 demonstration program costs to current PAFC costs:

- The New York Power Authority purchased a PC25C system in May 2002 for installation at the New York Aquarium. The equipment cost was $650,000 or $3,250 per kilowatt.
- A PC25 system began operation in October 2002 at South Windsor High School in Connecticut. A grant from the Connecticut Clean Energy Fund provided $2.3 million for the purchase, installation, and maintenance of this fuel cell system over 10 years. This equates to a total of $11,500 per kilowatt.
- Also in October 2002, pharmaceutical company Merck installed a PC25C unit at its New Jersey facility for a total of $910,000, which equals $4,550 per kilowatt. Assuming a equipment cost of $3,250 per kilowatt, the installation cost for this project was $1,300 per kilowatt.

These numbers justify the earlier claim that fuel cell equipment and installation costs are highly site-specific. They also confirm that the equipment cost paid for a PC25 fuel cell system is higher (at least $3,250/kW) than that paid by the DOD ($3,183/kW) for its PAFC demonstration program in the 1990s.

MCFC Demonstrations

Table 2-12 provides actual and projected cost data for the DFC®300 MCFC system under development by Fuel Cell Energy. This system provides an electric output of 250 kilowatts.

In August 2001, Los Angeles Department of Water and Power (LADWP) installed a DFC®300 system at their headquarters facility in downtown Los Angeles. The actual total demonstration cost was $3.2 million or $12,800 per kilowatt. LADWP paid $2.4 million in contract expenses to Fuel Cell Energy. In addition to the actual DFC®300 system cost, the contract included on-site support throughout the demonstration period, training for LADWP employees, installation assistance, maintenance services, and one month of acceptance testing following completion of the demonstration in December 2002. On top of the contract cost, LADWP incurred $800,000 (an additional 25%) in "installation costs," which included all engineering, site preparation, and construction for the DFC®300 system and for three Capstone microturbines that were installed at the same site.

In addition to the LADWP project, the following two MCFC installations were announced in Fuel Cell Energy press releases:

- In August 2002, Fuel Cell Energy announced that a DFC®300 power plant will be installed at Ocean County College in Toms River, New Jersey. The total value of the project is $1.65 million, or $6,600 per kilowatt.
- Fuel Cell Energy announced in October 2002 that two DFC®300 fuel cell systems will be installed at Zoot Enterprises' Galactic Park high-technology campus near Bozeman, Montana. The total value of the Zoot fuel cell project is $3.8 million, or $7,600 per kilowatt.

Table 2-12
DFC® 300 Total Installed Costs (Actual)

Item	LADWP 2001[19]		Ocean County College 2002[20]		LADWP 2003[21]		Zoot 2002[22]	
	($)	($/kW)	($)	($/kW)	($)	($/kW)	($)	($/kW)
Equipment	$2,400,000	$9,600			$1,225,000	$4,900		
Installation	$700,000	$3,200			$612,500[23]	$2,450		
Total	**$3,100,000**	**$12,400**	**$1,650,000**	**$6,600**	**$1,837,500**	**$7,350**	**$3,800,000**	**$7,600**

Source: Los Angeles Department of Water and Power and Fuel Cell Energy

Based on these numbers, it may be concluded that the 50% installation cost assumption used in the LADWP example is accurate. As was the case with past PAFC demonstrations, MCFC equipment and installation costs are highly site-specific. Fuel Cell Energy has made projections of future costs ranging from $900/kW to $1,500/kW

PEMFC and SOFC Demonstrations

While demonstrations of PEMFC and SOFC systems are plentiful, documented equipment and installation data are much more difficult to come by. This is because the PEMFC and SOFC technologies remain in earlier stages of demonstration and commercialization than the PAFC and MCFC technologies. This characteristic leads to prices that vary greatly and that are difficult to compare from one developer to another.

Some PEMFC and SOFC companies may provide a price for a demonstration over a specified period of time. For example, Nuvera is presently offering a one-year, turnkey demonstration of its 5-kW PEMFC system for about $30,000 per kilowatt. Other developers are further along and are able to offer systems for purchase with an established warranty. For example, Plug Power sells its 5-kW PEMFC system on a purchase order basis. Unfortunately, the equipment cost of this system is not published and it varies with each sale. In 2001, Siemens Westinghouse stated that the equipment cost of its 250-kW SOFC system was between $10,000-20,000 per kilowatt,

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[19] The $2.4 million equipment cost represents LADWP's contract cost to Fuel Cell Energy. In addition to the actual DFC®300 system cost, the contract included support services throughout the demonstration period. An additional $800,000 in installation costs were incurred by LADWP for the DFC system and three Capstone microturbines that were installed at the same site as the fuel cell system. Assuming that $100,000 represents the costs incurred for the microturbines, the remainder, $700,000, represents LADWP's engineering, site preparation, and construction for the fuel cell system. The actual cost split between the fuel cell and microturbine projects was not provided by LADWP.

[20] Ocean County College in Toms River, New Jersey, August 2002.

[21] The $1.225 million in actual equipment costs does not include any support services from Fuel Cell Energy. Based on the lessons learned and training provided by Fuel Cell Energy throughout the first demonstration, LADWP will install, operate, and maintain two new DFC®300 systems in 2003.

[22] Zoot Enterprises Galactic Park high-technology campus, Bozeman, Montana, October 2002.

[23] Assumes an installation cost equal to 50% of the equipment cost.

depending on the customer. With installation costs varying just as much, there is no sure way to estimate the installed costs of PEMFC and SOFC systems.

In summary, the actual costs reported for the installation of fuel cell systems range between $800 and $3,200 per kilowatt. The low-end figure of $800/kW represents the standard installation cost negotiated for the DOD PAFC demonstration program. It does not include any of the options that were commonly added in the installation of PC25 units for that program. It is estimated that the average installation cost for the DOD program was $1,479.

The high-end figure of $3,200/kW represents the installation costs incurred by LADWP last year in the deployment of a Fuel Cell Energy DFC®300 system. However, this figure includes engineering and site preparation for three microturbines that were installed at the same site. This may lead one to believe that the installation cost for just the fuel cell system may have been lower than $3,200. On the other hand, many of the installation support services provided by Fuel Cell Energy (e.g., worker training, assistance in with engineering and site preparation, etc.) were included in the equipment cost contract, which totaled $9,600 per kilowatt.

3
OPERATION AND MAINTENANCE COSTS

Like installation costs, operation and maintenance (O&M) costs for emerging technologies such as microturbines and fuel cells are relatively unpredictable and unproven compared to more mature DG systems. As microturbines and fuel cells approach full-scale commercialization, it is expected that the O&M costs will become more predictable and will approach levels of mature DG technologies.

O&M costs include all costs to keep the system operating properly, including:

- Consumables (lubricating oil, coolant, emissions control catalysts and reagents, etc.)
- Maintenance (labor and materials), scheduled and unscheduled

Fuel costs and the labor costs to operate the system (items such as monitoring system performance, checking liquid levels, and providing fuel) are not considered in this report. A sample worksheet can be found in **Appendix B** to assist in calculating operation and maintenance costs for a specific application.

Internal Combustion Engines

Typical maintenance activities for IC engines include regular oil and oil filter changes, routine inspections, top-end maintenance, and major maintenance. Operating costs for IC engines are primarily fuel costs, but the cost of operating and maintaining an emissions control system can be significant. For example, when the emissions control system uses selective catalytic reduction (SCR), the operating costs include the cost of urea (a source of ammonia) and the cost to replace the catalyst every five years or so. Natural gas engines generally require less frequent maintenance and inspection than diesel engines. Consequently, maintenance costs range from 0.005 to 0.01$/kWh for gas engines but range from 0.01 to 0.02$/kWh for diesel engines.

Scheduled maintenance for 60-Hz natural-gas-fueled engines in baseload/peaking applications includes the following:

- Routine Maintenance - Routine maintenance includes plug gap/change, oil and filter change, flush and replace coolant, and valve adjustments (around 2,000 hours)
- Top-End Overhaul - Top end overhaul includes rebuilding the heads and turbocharger along with safety system checks (around 20,000 hours)
- Major Overhaul - Major overhaul includes replacing the pistons, rings, cylinder liners, major bearings, coolers for lubrication oil and coolant, and generator check/rebuild (around 60,000 hours)

The recommended maintenance intervals vary considerably by manufacturer and by application. Engines used for standby power require shorter intervals. Combined heat and power applications and other applications with elevated jacket water temperatures will also require shorter intervals. If digester gas or landfill gas is used for fuel, the maintenance intervals are also shorter than for natural gas.

Table 3-1 estimates operating (consumables) costs of natural-gas IC engines. The labor portion of the operating costs (e.g., labor for monitoring system performance, and checking liquid levels) is not included in this table. The input data is based on a 2,000- kW_e, 60-Hz, 16-cylinder turbocharged-aftercooled natural gas fueled engine used for prime (continuous) power and operated 8,000 hours per year. The fuel cost of natural gas is based on $4.00/MMBtu (HHV) and 125,000 Btu (HHV) per gallon of gasoline equivalent (gge). The fuel consumption rate is based on a heat rate of 8,500 Btu/ kWh_e (LHV) and 114,000 Btu (LHV) per gge. The lubrication-oil consumption rate is 0.001 times the fuel consumption rate. The cost of consumables ($/hr) is the product of the rate of consumption and the cost per gallon. The cost in $/yr uses the annual operating hours, and the cost in $/kWh uses the output power.

Table 3-1
Cost of Consumables and Fuel for Natural Gas Engine Used for Prime Power[24]

Consumables	Units	Lubrication Oil	Fuel
Cost per gallon (or gge)	$/gal	8.00	0.50[25]
Consumption rate	gph	0.15[26]	149[27]
Cost of consumables[28]	$/hr	1.19	74.56
For 8,000 hr/yr	$/yr	9,544	596,491
For 2,000 kW_e	$/kWh	0.0006	0.0373

Table 3-2 estimates maintenance costs of natural-gas IC engines. The input data is based on the same engine as above. The routine maintenance materials include 400 gallons of lubrication oil at $8 per gallon, 500 gallons of coolant at $2 per gallon, $500 for a new oil filter, and $30 for each of 16 spark plugs. The top-end overhaul materials include a complete set of valves and a rebuilt turbocharger. The major overhaul materials include a complete set of pistons, rings, cylinder liners, major bearings, and coolers, as well as a rebuilt generator.

[24] Input data is based on a 2,000-kWe, 60-Hz, 16-cylinder, turbocharged-aftercooled, natural-gas fueled engine used for prime (continuous) power and operated 8,000 hours per year. Estimate of 10-Year Average Annual.
[25] Fuel cost of natural gas is based on $4.00/MMBtu (HHV) and 125,000 Btu (HHV) / gallon of gasoline equivalent (gge).
[26] Lubrication oil consumption rate is 0.001 times fuel consumption rate.
[27] Fuel consumption rate is based on 2,000 kW_e, 8,500 Btu/kW_eh (LHV), and 114,000 Btu (LHV) / gge.
[28] Cost of consumables is product of rate of consumption and cost per gallon.

Table 3-2
Maintenance Costs for Natural Gas Engine Used for Prime Power[29]

Maintenance	Units	Routine[30]	Top-end Overhaul[31]	Major Overhaul[32]	Annual Cost ($/yr)	Average Cost ($/kWh)
Maintenance Interval	hours	2,000	20,000	60,000		
Labor[33]	man-hours	40	80	320	235	
	$/event	4,000	8,000	32,000	23,467	0.0015
Maintenance Materials	$/event	5,000	10,000	100,000	37,333	0.0023
Total Maintenance	$/event	9,000	18,000	132,000	60,800	0.0038

Scheduled maintenance for 60-Hz diesel-fueled engines in baseload/peaking applications includes the following:

- Oil and oil filter changes (every 250 or 500 hours)
- Routine Maintenance - Routine maintenance includes flush and replace coolant, injector settings and valve adjustment (around 3,000 hours)
- Top-End Overhaul - Top end overhaul includes rebuilding the heads and turbocharger along with safety system checks (around 6,000 hours)
- Major Overhaul - Major overhaul includes replacing the pistons, rings, cylinder liners, major bearings, coolers for lubrication oil and coolant, and generator check/rebuild (around 15,000 hours)

As with gas engines, the recommended maintenance intervals vary considerably by manufacturer and by application.

Table 3-3 shows illustrative data for the operating (consumables) costs of a 2,000- kW_e, 60-Hz, 16-cylinder, turbocharged-aftercooled, diesel-fueled engine used for peaking power and operated 1,500 hours per year. A selective catalytic reduction (SCR) NOx emissions control system is included. The labor portion of the operating costs (e.g., labor for monitoring system performance, checking liquid levels, refueling) is not included in this table. The fuel consumption rate is based on 8,500 Btu/ kWh_e (LHV) and 128,750 Btu (LHV) per gallon of diesel. The lubrication-oil

[29] Input data is based on same engine as above. Estimate of 10-Year Average Annual.
[30] Routine maintenance materials include 400 gallons of lubrication oil at $8/gallon, 500 gallons of coolant at $2/gallon, $500 for oil filter, and $30 for each of 16 spark plugs.
[31] Top-end overhaul materials include a complete set of valves and a rebuilt turbocharger.
[32] Major overhaul materials include a complete set of pistons, rings, cylinder liners, major bearings, and coolers, as well as a rebuilt generator.
[33] Labor rate is $100/hour

consumption rate is 0.001 times the fuel consumption rate. The SCR system is assumed to consume 7 gph of urea. The cost of consumables is calculated in the same manner as above. The cost of fuel is by far the largest cost component (92%).

Table 3-3
Cost of Consumables and Fuel for a Diesel Engine Used for Peaking Power[34]

Consumables	Units	Lubrication Oil	Urea	Fuel
Cost per gallon	$/gal	8.00	1.50	1.00
Consumption rate	gph	0.13[35]	7	132[36]
Cost of consumables	$/hr	1.06	10.50	132.04
For 1,500 hr/yr	$/yr	1,584	15,750	198,058
For 2,000 kW_e	$/kWh	0.0005	0.0053	0.0660

Table 3-4 estimates maintenance costs of diesel-fueled IC engines with a SCR system for emissions control. The input data is based on the same engine as above. The oil and filter change materials include 400 gallons of lubrication oil at $8 per gallon and $500 for a new oil filter. The routine maintenance materials include 500 gallons of coolant at $2 per gallon. The top-end overhaul materials include a complete set of valves and a rebuilt turbocharger. The major overhaul materials include a complete set of pistons, rings, cylinder liners, major bearings, and coolers, as well as a rebuilt generator.

[34] Input data is based on a 3,000-kWe, 60-Hz, 16-cylinder, turbocharged-aftercooled, natural-gas fueled engine used for prime (continuous) power and operated 8,000 hours per year.
[35] Lubrication oil consumption rate is 0.001 times fuel consumption rate.
[36] Fuel consumption rate is based on 2,000 kWe, 8,500 Btu/kWeh (LHV), and 128,750 Btu (LHV) / gal.

Table 3-4
Maintenance Costs for a Diesel Engine Used for Peaking Power[37]

Maintenance	Units	Oil and Filter[38]	Routine[39]	Top-end Overhaul[40]	Major Overhaul[41]	Annual Cost ($/yr)	Average Cost ($/kWh)
Maintenance Interval	hours	500	3,000	6,000	15,000		
Labor[42]	man-hours	16	16	80	320	108	
	$/event	1,600	1,600	8,000	32,000	10,800	0.0036
Maintenance Materials	$/event	4,000	1,000	10,000	100,000	25,000	0.0083
Total Maintenance	$/event	5,600	2,600	18,000	132,000	35,800	0.0119

Table 3-5 estimates costs for maintaining an SCR emissions control system. The input data is based on the same engine as above.

Table 3-5
SCR Emissions Control System Maintenance and Consumable Costs for a Diesel Engine Used for Peaking Power[43]

SCR	Units	Catalyst	Annual Cost ($/yr)	Average Cost ($/kWh)
Maintenance Interval	hours	7,500		
Labor	man-hours	160	32	
	$/event	16,000	3,200	0.0011
Maintenance Materials	$/event	34,000	6,800	0.0023
Total Maintenance	$/event	50,000	10,000	0.0033
Total Maintenance + Consumables			25,750	0.0086

[37] Input data is based on same engine as above. Estimate of 10-Year Average Annual.
[38] Oil and filter materials include 400 gallons of lubrication oil at $8/gallon and $500 for oil filter.
[39] Routine maintenance materials include 500 gallons of coolant at $2/gallon.
[40] Top-end overhaul materials include a complete set of valves and a rebuilt turbocharger.
[41] Major overhaul materials include a complete set of pistons, rings, cylinder liners, major bearings, and coolers, as well as a rebuilt generator.
[42] Labor rate is $100/hour
[43] Input data is based on same engine as above. Estimate of 10-Year Average Annual.

Table 3-6 lists the fixed and variable O&M costs (per kW_e) for some typical applications of gas and diesel engine generator sets. For the most part, these O&M costs correspond to standard manufacturer's maintenance contracts, and tend to be higher than simple maintenance costs calculated above in **Tables 3-1 to 3-4**. It is reasonable for the manufacturer to charge a higher price than the basic maintenance costs calculated above for the following reasons:

- The manufacturer assumes all the risk to keep the system operational
- The manufacturer includes contingency costs in the rate structure
- The manufacturer may include an availability guarantee with liquidated damage payments
- The manufacturer's costs include overhead and perhaps profit

Table 3-6
ICE Operation and Maintenance (O&M) Costs

Engine Type	Gas Gen-set for Continuous Duty	Gas Gen-set for Prime Power	Gas Power Module for Peaking	Diesel Gen-set for Standby Power	Diesel Gen-set for Standby Power
Engine Reference	ICE1	ICE2	ICE3	ICE4	ICE5
Fuel	Natural Gas	Natural Gas	Natural Gas	Diesel	Diesel
Rating (kW_e)	1,300	1,400	1,250	2,000	2,000
Operation (hr/yr)	> 8,000	4,000-8,000	1,500-4,000	< 200	< 1,500
Load Factor (% of Full-load)	100%	100%	100%	60%	100%
O&M Cost Component	**Cost**	**Cost**	**Cost**	**Cost**	**Cost**
Fixed O&M Costs ($/yr/kW for materials)	$0	$0	$0	$0.75	$0
Fixed O&M Costs (hr/yr of labor)	0	0	0	50	0
Variable O&M Costs ($/kWh for materials)	$0.0075	$0.0085	$0.0100	$0.0130	$0.0187
Variable O&M Costs (hr/yr of labor)	Varies by year	Varies by year	Varies by year	Varies by year	Included above

The data in **Table 3-6** is based on a number of assumptions. The assumptions used for the ICE1 – ICE4 generator sets are:

- Fixed O&M costs apply only to diesel engines, and are estimated for typical standby service
- Labor cost is $45/hr
- Labor costs are normally higher on the Atlantic, Pacific, and Gulf coasts than inland

More specifically, the assumptions used for the ICE1 – ICE3 gas engines are:

- Variable O&M costs correspond to a standard manufacturer maintenance contract which includes dealer labor, manufacturer parts for standard maintenance and overhauls, 10-year coverage, all oil and filter changes, and coolant maintenance
- The O&M costs do not include inflation, fuel for test runs, or emissions testing
- Gas engines are typically run at 100% of rated load in continuous, prime, and peaking applications
- No load banks are needed for tests

The assumptions used for ICE4 diesel engines are:

- Variable O&M costs correspond to a standard manufacturer maintenance contract
- The O&M costs include only one oil and filter change
- The O&M costs do not include fuel for test runs, emissions testing, or dealer travel costs
- Diesel standby engines are typically run at 60% of rated load
- No load banks are needed for tests

The assumptions used for the ICE5 diesel engines are:

- The labor portion of the costs varies from 40% to 70%, depending upon maintenance activity
- The generator set is operated 1,500 hr/yr at 2,000 kW load (= 3,000,000 kWh/yr)
- The cost of the make-up oil is based on using 1 gallon per 1,000 gallons of fuel (or 0.138 gal/hr) at an oil cost of $8.00/gallon
- Oil change interval of 250 hours
- Tune-up interval of 1,500 hours
- Top-end overhaul interval of 4,250 hours
- Major overhaul interval of 10,000 hours
- Variable O&M cost is the annualized cost in $/kWh
- The O&M costs of enclosures, auxiliaries, switchgear, and controls are assumed negligible (there is no data for long-term costs)
- The cost of fuel burned by the engine is not included, but its cost was estimated to be $0.069/kWh based on burning 138 gal/hr at a fuel cost of $1.00/gallon
- The O&M cost of SCR NOx emissions control system is not included, but its O&M cost was estimated to be $0.0083/kWh based on replacing the catalyst every 5 years at a cost of $34,000 (actual cost varies with precious metal prices) and on consuming 7 gal/hr of urea at a cost of $1.50/gal

Figure 3-1 illustrates how the O&M cost (per kWh_e) differs with fuel type and differs by application. Labor costs vary considerably year-to-year. Gas-fueled generator sets are generally less expensive to maintain than diesel generator sets. Maintenance labor costs are comparable or slightly more than maintenance materials costs. Generator sets used for standby power have higher cost per kWh because they have much lower annual operating hours than for generator sets used for continuous duty.

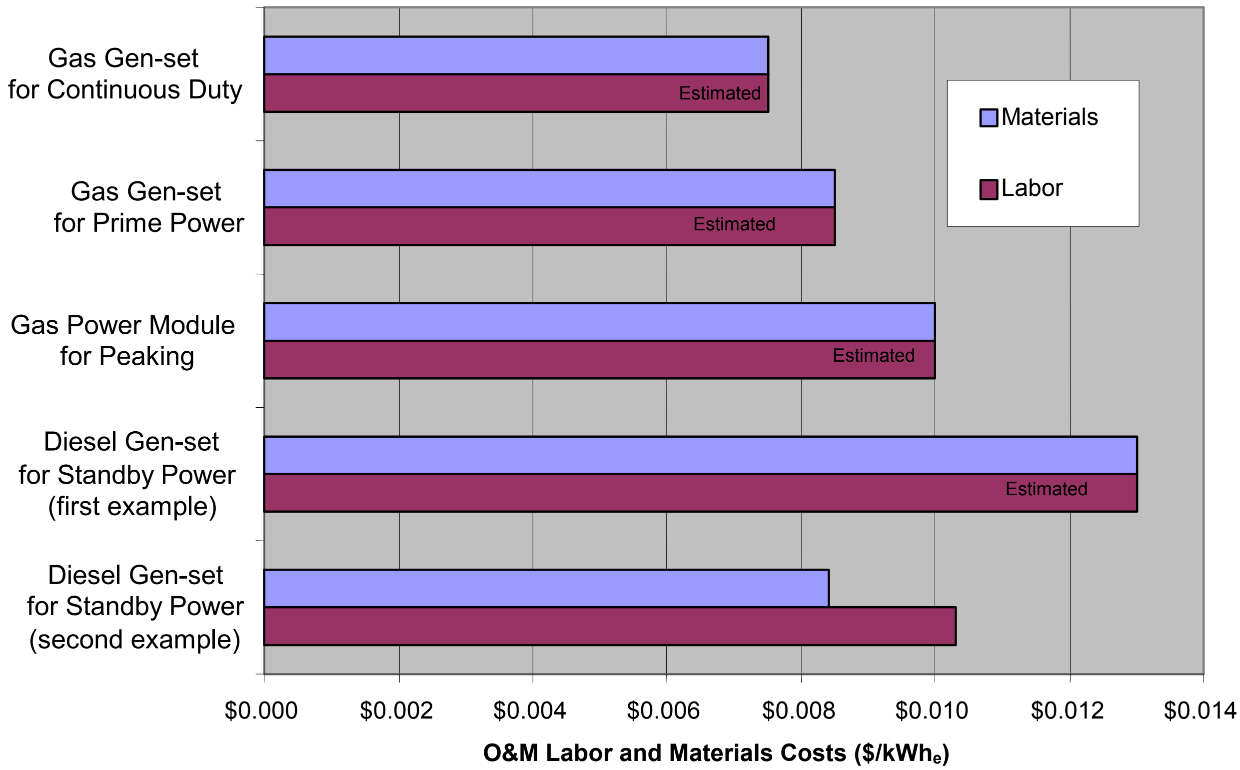

Figure 3-1
Typical ICE Operation and Maintenance (O&M) Labor and Material Costs ($/kWh$_e$)

Figure 3-2 shows the impact of an emissions control system on the distribution of O&M costs for ICE generator sets. This particular data set is a diesel generator set installed for standby power. The major O&M cost component is fuel; the emissions control system is about half the total of the routine, top-end, and major maintenance costs.

In summary, O&M costs of a 2-MW IC engine genset are in the vicinity of $0.01/kWh, including scheduled maintenance materials and labor, and excluding fuel and the labor to operate the system. The cost of diesel fuel is around $0.06 /kWh and the cost of natural gas fuel is around $0.03/kWh.

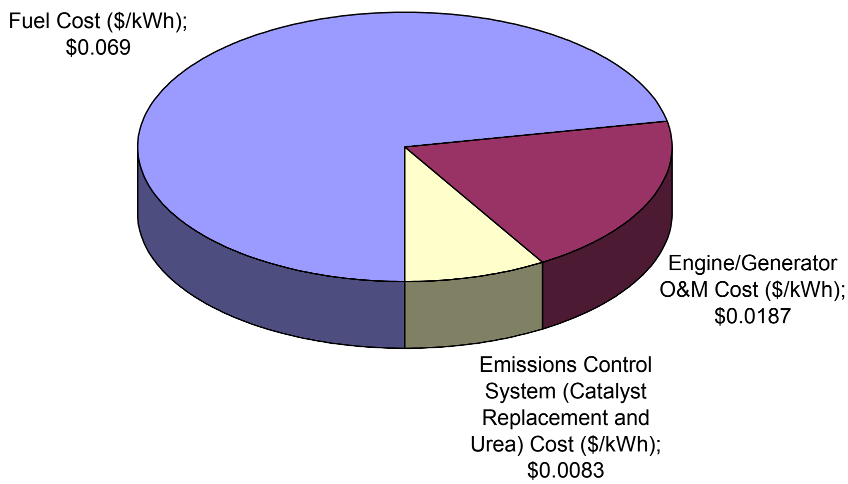

Figure 3-2
Typical Variable O&M Cost Breakdown for Diesel Engine Gen-set with SCR Emissions Control System ($/kWh$_e$)

Combustion Turbines

Typical maintenance activities for combustion turbines (CTs) include routine inspections, thorough inspections, and major overhauls. Operating costs for CTs are primarily fuel costs. Aeroderivative CTs tend to require greater maintenance than industrial CTs. That is, maintenance costs range from 0.4 to 0.6 ¢/kWh for heavy-frame industrial CTs and range from 0.6 to 0.8 ¢/kWh for aeroderivative CTs (from EPRI TR-113165). Alternatively, maintenance costs can be expressed as the sum of variable maintenance costs (cost amortized per kWh) and fixed maintenance costs (annual costs per kW) as indicated in **Table 3-7**. Variable costs in the table do not include fuel costs or the cost of replacement power during maintenance outages. The fixed O&M costs in this table include operating labor and are highly dependent of the plant's staffing philosophy. The higher cost in the table above is representative of smaller units (<5 MW), where the cost of operations is amortized over a lower capacity.

Table 3-7
Estimated Combustion Turbine O&M Costs Reported as $/kWh or as the Sum of Variable ($/kWh) and Fixed ($/kW-yr) costs

	$/kWh	Reported as Variable and Fixed
Industrial	0.004-0.006 $/kWh	0.002-0.003 $/kWh plus $14-24/kW-year
Aeroderivative	0.006-0.008 $/kWh	0.004-0.005 $/kWh plus $14-24/kW-year

Scheduled maintenance for combustion turbines in baseload or peaking applications includes the following:

- Routine inspection – Routine inspections (quarterly for CTs used for prime power) include a boroscope inspection of the compressor, combustor, and turbine, and recalibrations of sensors and controls (around 2,000 hours)
- Thorough inspection – Thorough inspections (annual for CTs used for prime power) include control checks, leak checks, and inspections of the generator windings, in addition to the boroscope inspections and recalibrations that are part of the routine inspections (around 8,000 hours)
- Hot gas path – Some manufacturers recommend a hot-gas path inspection every three years (around 24,000 hours)
- Major overhaul – A major overhaul entails dismantling and inspecting the entire system along with replacing major components as needed to add another 5 years to the life of the system. It includes a generator check/rebuild. Also, seals, bearings, combustor components, and blade assemblies are replaced/refurbished.

Most manufacturers recommend significant shortening of inspection intervals for turbines in severe service. Factors that can result in shortened inspection intervals include:

- Oil-fired operation
- Water injection for NOx control or power augmentation
- Frequent start-up/shutdown cycles
- Rapid loading rates
- Operation at a "peaking" rating

Table 3-8 illustrates a simplified methodology for estimating O&M costs (excluding fuel) of natural-gas-fired CTs. The input data is based on a 4,000- kW_e, 60-Hz, natural-gas-fired CT used for baseload (or prime or continuous) power and operated 8,000 hours per year. The cost of lubrication oil is assumed negligible. The routine inspection materials are miscellaneous supplies and minor parts. The cost of materials for a thorough inspection is a representative value for replacement parts. The major overhaul materials include the cost to rebuild the generator and the cost of the seals, bearings, combustor components, and blade assemblies that are typically replaced or refurbished. A CT maintenance contract will cost more than the total maintenance cost shown in **Table 3-8**, usually around $0.005/kWh.

Table 3-8
Maintenance Costs of a Natural-Gas-Fired CT Power Generation System Used for Prime Power

Maintenance	Units	Routine Inspection	Thorough Inspection	Major Overhaul	Annual Cost ($/yr)	Average Cost ($/kWh)
Maintenance Interval	hours	2,000	8,000	35,000		
Labor[44]	man-hours	12	84	960	351	
	$/event	1,200	8,400	96,000	35,143	0.0011
Maintenance Materials	$/event	1,000	10,000	250,000	71,143	0.0022
Total Maintenance	$/event	2,200	18,400	346,000	106,286	0.0033

Table 3-9 illustrates the same methodology as **Table 3-8** for estimating maintenance costs of a 4,000- kW_e, 60-Hz, natural-gas-fired CT used for peaking power and operated only 1,500 hours per year. The input data are based on the same engine as above. The annual cost is reduced compared to **Table 3-8** due to the lower annual operating hours.

Table 3-9
Maintenance Costs of a Natural-Gas-Fired CT Power Generation System Used for Peaking Power

Maintenance	Units	Routine Inspection	Thorough Inspection	Major Overhaul	Annual Cost ($/yr)	Average Cost ($/kWh)
Maintenance Interval	hours	2,000	8,000	35,000		
Labor	man-hours	12	84	960	66	
	$/event	1,200	8,400	96,000	6,589	0.0011
Maintenance Materials	$/event	1,000	10,000	250,000	13,339	0.0022
Total Maintenance	$/event	2,200	18,400	346,000	19,929	0.0033

[44] Labor rate is $100/hour

In summary, O&M costs of a 4-MW CT gen-set are approximately $0.005/kWh, including scheduled maintenance materials and labor, and excluding fuel and the labor to operate the system. For comparison, the cost of natural gas fuel is around $0.05/kWh.

Microturbines

Microturbines are similar to combustion turbines and require similar maintenance and consumables. It is assumed in this operation and maintenance discussion that microturbine systems will operate 8,000 hours per year in baseload applications. In determining their recommended maintenance schedules, Capstone and IR Energy Systems make the same assumption of 8,000 hours of operation, where Turbec assumes 6,000 hours of operation per year. The following maintenance schedules apply to all microturbine systems discussed in this report. The intermediate service, however, is only suggested by Capstone.

Yearly Inspections (or every 8,000 hours of operation)

- General inspection
- Change of consumables, oil and water (if necessary)
- Change oil and oil filter in the gas compressor (if applicable)
- Replace air and fuel filters

Intermediate Service (every 2 years or 16,000 hours of operation)

- Clean or replace the injectors, igniter, and thermocouples

Major Overhaul (every 5 years or 40,000 hours of operation)

- Replace entire combustion chamber
- Refurbish engine
- Replace bearings in lubrication oil pump, ventilation fan, and buffer air pump

Microturbine system life is estimated at 10 years or 80,000 hours of operation (60,000 hours for Turbec's system). This has yet to be proven, however. Capstone's longest running commercial unit has accumulated 26,000 hours of operation (as of mid-2002).

Table 3-10
Estimated Microturbine System Operation and Maintenance Costs

Microturbine Manufacturer	Power Output	O&M[45] Cost ($/kWh)	Basis for O&M Costs
Bowman Power Systems	80 kW	0.011 – 0.013	N/A
Capstone Turbine	30 kW 60 kW	To Be Determined	To Be Determined
Elliott Energy Systems	80 kW	0.007 – 0.011	N/A
IR Energy Systems	70 kW	0.011	Based on a $6250/year maintenance package and 8,000 hours annual operation
Turbec AB	100 kW	0.011	Based on 6,000 hours annual operation and a full service maintenance package (parts only are estimated to cost $0.007/kWh)

Manufacturers are beginning to offer set-price maintenance service packages. O&M costs presented herein for microturbines are, at best, estimates of the potential mature cost. The maintenance schedules themselves are also not proven. The life of the microturbine system in commercial operation has not been verified.

Turbec plans to offer two service packages and is currently working to set up a distribution and service network within the United States for maintenance support. The first package, a comprehensive maintenance plan, will cover all parts and labor for regularly scheduled maintenance. This package is estimated to cost $0.011 per kilowatt-hour. The second package is for parts only, and its estimated cost is $0.007 per kilowatt-hour.

In summary, microturbine O&M costs have yet to be verified, however, manufacturers are consistently estimating costs or beginning to offer complete maintenance packages at $0.011 per kilowatt-hour.

Fuel Cells

Fuel cell systems have not yet been widely deployed, so operation and maintenance costs are difficult to define and can be inconsistent from one fuel cell to the next. Part of the ongoing fuel cell development process is to create components that have longer lifetimes and therefore reduce the O&M costs. This section provides an overview of fuel cell components and maintenance schedules, and then summarizes O&M costs based on field test data.

[45] O&M does not include fuel or equipment depreciation

It can be helpful to investigate the components that make up a particular fuel cell system in order to understand the potential O&M requirements. Specific system components can vary significantly by fuel cell technology and by each individual company's stack and system design. Common components include:

- *Desulphurization unit* – Sulphur can poison the catalysts used in fuel reformers and fuel cell stacks. It also contributes to sulphur oxide (SO_x) emissions. Hence, a desulphurizer is required to remove sulphur from the fuel.
- *Fuel compressor* – Depending on the fuel cell system design and on the pressure of the fuel available at the installation site, a fuel compressor may be required.
- *Air filter* – A filter is used to remove larger particulate matter from the air before it enters the fuel cell system.
- *Air compressor or blower* – Depending on the design of the fuel cell system, a compressor may be required to boost the air pressure before it enters the fuel cell system. In some cases, a simple fan or blower may be used.
- *Water filter or purification system* – For fuel cell systems that consume water for the reforming process, it is important the added water is free of impurities that may damage the catalysts used in the reformer and stack. In some cases, a simple water filter is used. In other cases, a more complex water purification system (e.g., reverse osmosis) may be required.
- *Water pump* – A pump is required to pump the water into the reformer.
- *Coolant pump* – A pump is required to circulate water or a coolant through a heat exchanger to maintain the temperature of the fuel cell stack.
- *Fuel reformer* – The reformer consists of several chemical reactors to convert the fuel into a hydrogen-rich gas. Because the reformer typically operates at higher temperatures than the rest of the fuel cell system, each of its components is heavily insulated.
- *Fuel cell stack* – In the fuel cell stack, hydrogen from the reformer reacts with oxygen from air to produce direct current (DC) electricity, heat, and water.
- *Heat exchangers* – Several heat exchangers are typically used throughout the fuel cell system. Waste heat from the reforming process and from the fuel cell stack may be used to preheat the fuel and air before it enters the reformer. A heat exchanger is also required for maintaining stack temperature. A radiator-type heat exchanger with a fan may be used to exhaust excess heat from the system.
- *Power conditioning unit* – The power conditioning unit (PCU) converts the DC electricity generated in the fuel cell stack into alternating current (AC) to meet the specifications required on site. In many cases, the PCU is also responsible for sensing the electric grid, ensuring that the AC electricity from the fuel cell system is synchronous with the electric grid, and switching from grid-parallel to grid-independent operation automatically.
- *Heat recovery equipment for combined heat and power (CHP) applications* – The additional components utilized for CHP systems varies by company and by site requirements. CHP applications may require additional heat exchangers, a water storage tank, an absorption chiller, additional system controls, etc.

- *System controls* – The fuel cell system controls are responsible for ensuring that the system components communicate properly with each other and with the outside environment (e.g., human beings, external sensors, etc.).
- *Piping, valves, and other balance of plant (BOP)* – In addition to the major components listed above, fuel cell systems incorporate many more parts that are typically lumped together into BOP. BOP may include piping (metal and/or plastic), connectors, screws, nuts, bolts, valves (manual, solenoid, etc.), thermocouples, flow meters, and many other small items.

The maintenance required for each of the system components listed above can vary with a number of factors. Over time, it is likely that fuel cell developers will be able to perfect the selection of materials and system designs to eliminate inconsistencies in component life among technology types, fuel types, and climate. But for now, these items should be considered when preparing for the deployment of a fuel cell system:

- *Technology type* – The operating temperatures and the chemistry within the fuel cell system can impact the life of the components. For example,
  - The main point of failure in a PEMFC stack is the membrane electrode assembly (MEA). While most PEMFC developers are projecting a stack life of five years, no MEA developer has actually tested an MEA for five years. Rather, accelerated testing methods have been used to simulate 40,000 hours of operation on an MEA. The validity of these accelerated tests in determining actual life remains to be seen.
  - The durability issue in an SOFC stack is the interconnect between the cells. Because SOFC is a high-temperature fuel cell technology, the interconnect material must be able to handle thermal cycling. In years past, degradation of metallic interconnects lead to stack failure. In recent years, some SOFC developers have successfully incorporated more advanced metallic interconnects. Others have opted to utilize ceramic materials for both the cells and the interconnects.
  - Decades ago, the major issue with MCFC stack technology was the highly corrosive and mobile nature of the electrolyte. This lead to material problems, particularly mechanical and chemical stability, which reduced the life of the stack. Like SOFC, there were also problems with thermal cycling and sealing stack manifolds. This was due to the fact that there were a number of materials with different coefficients of thermal expansion heated and cooled together in the stack. Fuel Cell Energy, the leading MCFC developer, has claimed to eliminate these issues through better material selection and improved stack design.
  - Durability and reliability of PAFC technology has been proven over the past decade with the installation and operation of more than 200 PC25 fuel cell systems manufactured by UTC Fuel Cells. The company has continually improved the PAFC stack design based on information learned from these demonstrations. Some of the thirty PC25 systems installed by the DOD between 1994 and 1997 continue to operate today with the original fuel cell stack. In fact, in the DOD demonstrations, the inverters and reformers within the PAFC systems failed more often than the stacks. In order to lengthen the life of stack even further, it will be necessary to suppress the corrosion rate of carbon, a major PAFC material.

- Fuel type – Due to different chemistry, component lives may vary among the different fuels that may be suitable for an individual fuel cell system. For example, propane fuel typically has higher sulphur content than natural gas. Therefore, the life of the desulphurizer may be shortened when the fuel cell system is operated on propane. The varying elements in different fuels may also have a poisoning effect on catalysts used throughout the system. It is also important to note that failure of one component may have a domino effect and lead to a shortened lifetime of all downstream components.
- Climate – Altitude, heat, cold, rain, snow, and other climate conditions can impact the operation and performance of a fuel cell system. Any change in performance may also lead to a change in the lifetime of system components.

Fuel Cell Maintenance Schedules

Fuel cell maintenance schedules may be derived from field experience with PAFC technology (more than 200 systems have been installed worldwide since the early 1990s). For the PAFC demonstration program conducted by the Department of Defense (DOD), maintenance contracts were purchased from UTC Fuel Cells for each of the PC25 units installed in order to ensure continued operation of the systems.

Some maintenance tasks were scheduled on the DOD's PAFC fleet as often as every 2,000 hours of operation (or four times per year). Other tasks were performed as infrequently as once every 40,000 hours of operation (or once every five years). The following sections, which summarize these maintenance requirements, are taken directly from a DOD report.[46] Although other fuel cell products have not been deployed in quantities as large as the PC25, most fuel cell developers are predicting maintenance schedules similar to the one that follows.

Water Treatment System

The water treatment system purifies water recovered from the condensate from one of the heat exchangers and the cell stack cooling loop. Routine maintenance activities required for this system occur quarterly and annually:

1. Quarterly maintenance
    a. Replace mineral demineralizer beds
    b. Clean water tank
    c. Clean water filters

[46] "Phosphoric Acid Fuel Cells," ERDC/CERL TR-00-33 47, 2000.

2. Annual maintenance
    a. Clean deaerator column
    b. Pump maintenance

Process Air and Fuel Supply Systems

The process air system provides air to the cathodes and provides combustion air to the reformer. The fuel processing system converts natural gas into a hydrogen-rich fuel for the stack. Routine maintenance activities required for this system occur quarterly and annually:

1. Quarterly Maintenance: Replace air filters
2. Annual Maintenance
    a. Lubricate bearings on process air blower
    b. Clean condenser
    c. Check spark plug
    d. Check flame sensor

Ancillary Cooling System

The ancillary cooling system provides cooling for the power conditioning system by means of the remote cooling module and the power module heat recovery loops. Routine maintenance activities required for this system occur quarterly and annually:

1. Quarterly Maintenance: Lubricate pump bearings
2. Annual Maintenance
    a. Pump maintenance
    b. Clean filter
    c. Analyze glycol solution

Cell Stack Cooling System

The cell stack cooling system maintains the stack temperature, supplies process steam to the fuel processing system, and cools the reformed fuel. Routine maintenance activities required for this system occur annually and bi-annually:

1. Annual Maintenance: Inspect accumulator
2. Bi-Annual Maintenance
   a. Pump maintenance
   b. Check flow switch
   c. FO400 Replacement.

Compartment Ventilation System

The compartment ventilation system provides thermal control of the interior of the power plant module and prevents the build-up of combustible gases. Routine maintenance activity required for this system occurs quarterly:

1. Quarterly Maintenance: Replace air filters

Electrical System Assembly

The electrical system consists of a converter (changes direct current power into alternating current power), controls, auxiliary electric loads, and monitoring system. Routine maintenance activities required for this system occur annually and bi-annually:

1. Annual Maintenance
   a. UPS functional check
   b. Check panel boards
   c. Test automatic transfer switch
   d. Check motor starters
   e. Provide power conditioner maintenance
   f. Calibrate I/O devices
   g. Check power supply voltage
2. Bi-annual Maintenance
   a. Replace air conditioning filter
   b. Coolant flow switch (FS400) and FO400 replacement.

Cell Stack

Throughout the life of the cell stack, the electrical output will decrease for a given fuel consumption rate. As this occurs, the quantity of heat produced will increase. Once the cell stack has operated for more than 40,000 hours, the performance will have dropped noticeably. At this point, the operating efficiency of the fuel cell should be continuously monitored. When the electrical efficiency has dropped to the point where the cost of electricity produced by the fuel cell no longer meets the cost advantage of purchasing electricity from the utility, the cell stack should be replaced.

Fuel Cell O&M Costs

O&M cost estimates for fuel cell systems may also be derived from field experience with PAFC technology. For the DOD PAFC demonstration program, UTC Fuel Cells included one year of maintenance in the initial equipment cost of the system ($3,986 per kilowatt for the standard package without options). For each of the fuel cell systems installed, DOD then purchased an additional 44 months of maintenance from UTC Fuel Cells at the fixed contract costs shown in **Table 3-11**. These contracts included the materials and support for all scheduled and unscheduled maintenance required to keep the PC25 units operating; however, the contracts did not include fuel cell stack replacement (typically required after 40,000 hours of operation).

Table 3-11
DOD Fuel Cell Program – PC25 O&M Costs

Maintenance Contract	Fixed Contract Cost ($)	Estimated Cost per kWh[47]
First year	Included in System Cost	---
Two additional years	$52,936	1.65-6.62 ¢
Each additional month	$2,263	1.70-6.79 ¢

Although the costs in **Table 3-11** represent the maintenance contract costs paid by DOD, these numbers do not truly represent the actual O&M costs incurred throughout the first 56 months of operation of each PC25 system. These actual costs are presently not published or available to us. However, DOD recently began a project to investigate the actual O&M costs of one of the PC25 systems that was installed as part of the demonstration program. It will then be possible to break the actual maintenance costs into fixed and variable O&M components and to compare them the price that was paid for the maintenance contract.

For comparison, the DOE conducted a study, in part to estimate the O&M costs for fuel cells. The estimates in this report were based on comparisons with other DG systems, primarily IC engines. Therefore, data from this report should be viewed purely as estimates or projections of what fuel cell O&M costs should or could be, rather than on data from actual installations. The goal was to

[47] Best case scenario assumes 8,000 hours of operation per year at the maximum electric output of 200 kW. Worst case scenario assumed 4,000 hours of operation per year at 100 kW. This cost excludes stack replacement.

estimate the near-term (2004) costs of O&M for fuel cells. The estimates for fixed and variable O&M costs of the different fuel cell technologies from this DOE report are shown in **Table 3-12**.[48] These costs are based on 8,000 annual operating hours in terms of annual electricity generation. The fixed component is based on an interpolation of IC engine manufacturer estimates and applied to fuel cells. The variable component includes inspections and minor procedures that would typically be conducted (today) by the fuel cell developer under the terms of a maintenance contract. For the purpose of this example, the variable O&M cost component is estimated at 60% of IC engine service contracts. The cost of fuel cell stack replacement is estimated separately, based on information provided by developers of the different fuel cell technologies.

Table 3-12
Estimated/Projected Fuel Cell O&M Costs

System Description	System 1	System 2	System 3	System 4
Fuel Cell Type	PAFC	PEMFC	MCFC	SOFC
Rating (kW)	200	200	250	100
Operation (hrs/yr)	8,000	8,000	8,000	8,000
O&M Cost Component				
Variable Service Contract (¢/kWh)	0.87	0.87	0.72	1.02
Variable Consumables (¢/kWh)	0.02	0.02	0.02	0.02
Fixed (¢/kWh)	0.08	0.08	0.06	0.13
Stack Replacement (¢/kWh)	1.93	1.32	3.50	1.25
Net O&M Cost (¢/kWh)	**2.90**	**2.29**	**4.30**	**2.42**

Source: "Gas Fired Distributed Generation Technology Characterizations, Fuel Cell Systems," April 2002 Draft, National Renewable Energy Laboratory

The information in **Table 3-12** states that the two driving costs of fuel cell maintenance are: (1) the variable service contract costs (~ 35%), which includes inspections, minor procedures, and parts and (2) the stack replacement cost (~ 60%). **Figure 3-3** illustrates this relationship between the O&M cost components.

[48] "Gas Fired Distributed Generation Technology Characterizations, Fuel Cell Systems," April 2002 Draft, National Renewable Energy Laboratory

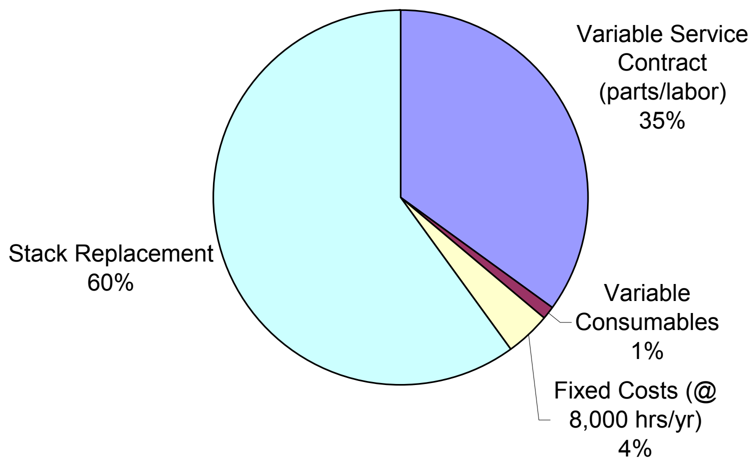

Figure 3-3
Representative Breakdown of O&M Costs for Fuel Cell Systems

Note that the O&M costs, excluding stack replacement range between 0.80 and 1.15 cents (100 cents = $1) per kWh, compared to a minimum of 1.65 cents/kWh from the DOD data. Therefore, the results from **Table 3-12** are likely optimistic estimates for the near term.

In summary, the specific maintenance costs for fuel cell systems are not widely available. Based on the data presented, maintenance costs for fuel cells are estimated to be in the range of 1.65 – 6.79 cents per kilowatt-hour, excluding stack replacement. Assuming a high capacity factor (i.e., operation at full system output for 8,000 hours per year), the range can be significantly narrowed to about 1.65 – 2.5 cents per kWh. However, stack replacement is by far the largest contribution to the O&M cost of a fuel cell system and can add 1.25 to 3.5 cents per kilowatt-hour. When the stack replacement is included, the maintenance cost range is 2.90 – 6.0 cents per kWh.

4
COMPARISON OF DG AND HVAC INSTALLATION, OPERATION, AND MAINTENANCE COSTS

Installation, operation, and maintenance (IOM) costs for combustion turbines and internal combustion engines are relatively stable and competitive because of the mature nature of these technologies. The IOM costs for both microturbines and fuel cells tend to be relatively high because of the prototype or emerging nature of these technologies. What will be the costs of microturbines and fuel cells when they do become mature and are produced in larger quantities? Is it reasonable to assume these costs will be reduced to similar levels as the small CTs and ICEs?

The potential market for DG systems includes residential and commercial buildings. If small DG technologies begin to be produced in large quantities and for on-site installation, is it reasonable to project that their IOM costs may approach those of residential and commercial building energy technologies? This chapter looks briefly at the IOM costs of HVAC technologies and compares them to the IOM costs of DG technologies.

Products in Mature Industries

Residential and commercial buildings in the US utilize heating, ventilating, and air-conditioning (HVAC) technologies to provide occupant comfort. Technologies such as heat pumps and chillers are mass-produced in relatively high quantities. Heat pumps and chillers are relatively complex energy conversion devices that require professional installation and maintenance.

Typical residential split system heat pumps include an outdoor unit and an indoor cooling coil. The outdoor unit is placed on a small concrete pad. It is connected to the indoor coil by two refrigerant lines. An electrical cable (208/230-volt) is required to power the motor, along with a “Unit Disconnect” as required by the National Electric Code. Local vendors typically have very efficient installation methods and focus on one or possibly two standard configurations. The result is a very low cost installation.

Heat pumps provide heating and cooling to both residential and small commercial buildings. Heat pumps range in size from very small (1.5 tons) to approximately 50 tons. On the order of 1 million heat pumps are shipped from factories each year in the U.S. For a standard residential heat pump (5 tons), the installation cost is approximately $1500 ($300/ton). For a larger, 50-ton system the installation cost is approximately $18,000 ($360/ton). Maintenance costs for small heat pumps are very small, approximately $200/year, and for the larger heat pump it can be as much as $1000 - $1500/year.

Chillers are large cooling systems for commercial buildings. They generally require site-specific engineering and custom installation. Electric chillers are comprised of an electric motor that drives a compressor, a condenser, an evaporator, and other components for operating the vapor-compression refrigeration cycle. Gas-fired chillers are either engine-driven (a gas engine replaces the electric motor in the vapor-compression refrigeration cycle), or absorption chillers which are based on the absorption, or heat-activated thermodynamic cycle. Chillers require a significant concrete pad or enclosed room for installation. In some cases they are installed on building rooftops via crane or helicopter.

Table 4-1 shows the equipment cost, installation cost, and footprint for two sizes of chiller systems. Total installed costs for chillers are roughly twice the equipment-only cost. The gas-fired chillers are roughly twice the cost of the electric chillers. The small (200-ton[49]) chiller is approximately suitable for a 100,000 square foot office building and the large (1000-ton) chiller is approximately suitable for a 400,000 square foot office building. For the smaller system it costs roughly $80 - $100K to install the chiller, and for the larger system the cost is $300 - $400K.

Table 4-1
Installation Costs and Footprint for Commercial Building Chillers

	200-ton Chiller		1000-ton Chiller	
	Electric*	**Gas****	**Electric**	**Gas**
Equipment Cost	$400/ton	$700/ton	$300/ton	$500/ton
Installed Cost	$800/ton	$1200/ton	$600/ton	$900/ton
Installation Cost	$80,000	$100,000	$300,000	$400,000
Footprint	94 ft^2	94 ft^2	166 ft^2	338 ft^2

* The electric chiller is an electric centrifugal chiller

** The gas chiller is gas absorption

(Source: EPRI Electric Chiller Handbook)

Maintenance costs for chillers are shown in **Table 4-2**. Maintenance costs for the electric and gas absorption chillers are similar, but the gas engine-driven chiller has significantly higher maintenance costs. The gas engine chiller required higher maintenance because an internal combustion engine rather than an electric motor drives the vapor compression cycle. The IC engine requires oil and filter changes and other items not required by the electric chillers. The absorption chiller also has lower maintenance than the engine-driven chiller as no engine or motor is required for the absorption cycle.

[49] "Ton" refers to a refrigerant ton which equals 12,000 Btu/hr

Table 4-2
Maintenance Costs for Commercial Building Chillers

	200-ton Chiller	1000-ton Chiller
Electric Chiller	$37/ton/year $7400/year	$20/ton/year $20,000/year
Gas Engine Chiller	$120/ton/year $24,000/year	$65/ton/year $65,000/year
Gas Absorption Chiller	$35/ton/year $7000/year	$18/ton/year $18,000/year

Source: EPRI Electric Chiller Handbook

HVAC and DG Installation Cost Comparisons

The installation costs of HVAC and DG equipment can be compared based on the size (physical and/or power input/output) of the equipment. **Table 4-3** lists a mixture of HVAC and DG technologies from small residential systems to those suitable for large commercial buildings. The products listed in the table are sorted by size in kW for the DG systems and ton for heat pumps and chillers. For purposes of this comparison, it is suggested that the comparably sized equipment (physical and energy) should require approximately the same cost to install and maintain. There are both similarities and differences between DG and HVAC system installations. However, if the potential market for DG systems is residential and commercial buildings, then equipment purchasers may expect or demand installation costs to be in line with other energy equipment such as HVAC systems. Since HVAC systems are installed in such large quantities their installation costs are relatively well known and represent good target prices for DG systems.

The variables in **Table 4-3** include system size in kW for DG equipment and in refrigerant tons for the heat pumps and chillers. For the purposes of this report we can assume the size of 1 refrigerant ton will require approximately 1 kW of power (for an electric chiller the kW/ton is approximately 1). Therefore, for example, a 5-ton heat pump is assumed to be comparable to a 5-kW DG technology. The footprint (square feet) and weight (lbs) of many systems is also listed.

The first four rows of **Table 4-3** can be considered residential systems. The installation costs for heat pumps and central A/C systems are relatively low at between $1500 and $2500 ($300 - $250/ton). Installation costs for the residential PEM fuel cell are unknown, primarily because these systems are not yet commercially available and each installation is unique.

Table 4-3
Installation Cost Comparisons* for Various HVAC and DG Technologies

	Size (kW)	Size (ton)	Footprint (sq. ft.)	Weight (lbs)	Installation Cost ($)	Installation Cost ($/kW)	Installation Cost ($/ton)
Heat Pump	-	5	9	350	1,500	-	300
PEM Fuel Cell**	7	-	18	-	*10,000*	1429	-
Split System A/C	-	10	15	700	2,500	-	250
Heat Pump	-	10	15	800	2,500	-	250
Microturbine	30	-	20	1600	71,250	2375	-
Heat Pump	-	50	20	-	18,000	-	360
Small Electric Chiller	-	200	94	20,500	80,000	-	400
Small Gas Chiller	-	200	94	19,400	100,000	-	500
MCFC Fuel Cell	250	-	200	-	500,000	2000	-
SOFC Fuel Cell**	250	-	205	60,000	*500,000*	650	-
IC Engine	365	-	84	13,860	91,250	250	-
IC Engine	750	-	53	22,500	187,500	250	-
Large Electric Chiller	-	1000	166	41,540	300,000	-	300
Large Absorption Chiller	-	1000	338	106,280	400,000	-	400
Combustion Turbine	5500	-	231	65,000	1,980,000	360	-
IC Engine	5920	-	237	179,000	1,480,000	250	-

* The technologies in this table are sorted by size in kW or Ton

**Installation costs for this fuel cell are estimates/projections from DOE report

Source: *Means Mechanical Cost Data, EPRI Electric Chiller Handbook, EPRI Heat Pump Manual,* and *Mechanical Estimating Guidebook*

The remaining technologies (>10 tons or kW) are suitable for commercial buildings ranging from small offices (~5000 square feet) to very large (>500,000 square feet) offices or retail complexes. The installation costs for these technologies range from $18,000 for a 50-ton heat pump to nearly $2 million for a large 5.5 MW combustion turbine. Excluding the cost for the emerging technologies (microturbines and fuel cells) the cost per unit (kW or ton) is consistently in the range of $250 - $400/unit with the exception of the small gas chiller at $500/ton. An overall good target for emerging DG technology installation costs would be in the range of $250-$400/kW.

DG Installation Cost Target: $250 - $400/kW

HVAC and DG Operation and Maintenance Cost Comparisons

The operation and maintenance costs (non-fuel) for residential HVAC technologies are low (generally less than $200/year). **Table 4-4** includes a listing of various HVAC and DG technologies and their maintenance costs. As with installation costs, the O&M costs for the chillers and heat pumps are relatively well known and consistent from one installation to the next. Similarly, the IC engine and combustion turbine DG technology O&M costs are pretty well defined.

Table 4-4
Comparisons of O&M Costs for Various HVAC and DG Technologies

	Size (kW)	Size (ton)	O&M Cost ($/year[50])	O&M Cost ($/kW/year)	O&M Cost ($/ton/year)
Heat Pump	-	5	160	-	32
PEM Fuel Cell*	50	-	2600	52	-
Microturbine	70	-	6250	89	-
Electric Chiller - Small	-	200	6000	-	30
Gas Absorption Chiller – Small	-	200	6400	-	32
Gas Engine Chiller - Small	-	200	20,000	-	100
PA Fuel Cell	200	-	46,400	232	-
MC Fuel Cell	250	-	86,000	344	-
Electric Chiller - Large	-	1000	20,000	-	20
Gas Engine Chiller - Large	-	1000	60,000	-	60
IC Engine (Continuous)	1300	-	194,480	150	-
IC Engine (Peaking)	1300	-	72,930	56	-
Combustion Turbine	5500	-	132,000	24	-

* PEM Fuel Cell O&M costs are projections from EPRI Report No. 1001243

[50] Assumes 8000 hours of operation, except for peaking IC engine

The O&M costs from the table can be grouped into three categories:

- Low O&M Costs – Non-engine based mature technologies including electric chillers, heat pumps, absorption chillers, and combustion turbines. O&M cost range: $20 - $32/(ton or kW), or $0.0025 - $0.004/kWh.
- High O&M Costs – Engine-based technologies. Includes IC engines for DG and engine-driven chillers. O&M cost range: $50 - $100/(ton or kW), or $0.006 - $0.0125/kWh.
- Emerging Technology O&M Costs – Fuel cells and microturbines. O&M cost range: > $100/(ton or kW), and as high as $0.06/kWh. Note the microturbine listed in **Table 4-4** is below this level, but other microturbines are still being developed and these prototype machines require significantly higher O&M.

Projections for Microturbines

The current (2002) costs for installing a microturbine (30kW) are approximately $71,250 (based on installations in the EPRI Microturbine Field Demonstration Program), or $2375/kW. The projected future cost for installing the same microturbine is $18,000, or $600/kW. The reduction in cost comes from a reduction of labor costs in all aspects of the installation, but primarily the electrical and fuel supply systems. This installation cost ($600/kW) is approaching the range of $250 - $400 of the other mature technologies and therefore seems like both a realistic and acceptable target.

The non-fuel operation and maintenance costs for microturbines are considered to be approximately 1.1 cents/kWh. These costs remain to be validated by significant experience, but most of the manufacturers are basing annual maintenance contracts on these numbers. Assuming these values, the range is $66/kW/yr - $88/kW/yr, based on 8000 hours of operation per year. At this level the microturbine is in the range of engine-driven technologies (see **Table 4-4**).

Projections for Fuel Cells

The current (2002) installation costs for fuel cells are estimated to be approximately $650/kW. These costs are generally higher that comparable HVAC or mature DG technologies. The goal should be to reduce this number by at least 50%.

The current O&M costs for fuel cells are estimated to be in the range of $232 - $344/kW/year (based on 8000 hours of operation, see **Table 4-4**) for the phosphoric acid and molten carbonate fuel cells. There have been a variety of studies projecting the future costs of fuel cells (primarily equipment costs). For example, the projected value for the PEM fuel cell listed in Table 4-4 is $52/kW/year.   However, most projected values are optimistic. A good initial target for fuel cell O&M costs would be to get them in the range of $50 - $100/kW/year (or close to $0.01/kWh), which would be comparable to engine-based technologies.

5 SUMMARY AND CONCLUSIONS

Installation, operation, and maintenance (IOM) costs are a significant part of an overall distributed generation project. This report has reviewed and characterized the current (2002) IOM costs for internal combustion engines, small combustion turbines, microturbines, and fuel cells. Often, many aspects of the IOM costs are overlooked or left out of installed cost estimates. In addition, IOM cost comparisons were made between distributed generation (DG) and heating, ventilating, and air conditioning (HVAC) systems.

The IOM costs can vary significantly due to many factors including equipment size, local labor rates, technology add-ons (e.g., heat recovery), and others. IOM costs for mature technologies are lower and have less variation than IOM costs for emerging technologies.

Example calculations are included in the Appendices to provide a template for calculating custom IOM costs for specific installations. The Appendices also include data tables illustrating how IOM labor rates vary among US cities and among the various labor categories.

Installation Cost Comparison

Installation costs for emerging technologies such as microturbines and fuel cells are relatively high and unpredictable compared to more mature DG systems, such as internal combustion (IC) engines and combustion turbines. Fuel cell and microturbine installation costs are currently $2000/kW or more depending on many variables. On the other hand, installation costs for an IC engine being used for backup power can be as low as $158/kW. Installation cost values used in this report exclude the cost of the generation module.

Installation costs can have significant variation from one project to another. **Table 5-1** shows the current (2002) installation cost ranges for the four DG technologies covered in this report.

Table 5-1
Installation Cost Ranges ($/kW)

DG Technology	Installation Cost Range ($/kW)[51]
Internal Combustion Engine[52]	160 - 300
Combustion Turbine[53]	200 - 1000
Microturbine[54]	1000 - 2600
Fuel Cells[55]	800 – 3200

Selected observations include:

- IC engine installation costs are consistently lower that other DG technologies
- The per-kW installation cost for CTs is significantly higher for smaller systems (e.g., 1 MW) that for the larger systems (e.g., 25 MW). Heat recovery and/or emissions control can add significantly to the cost.
- Microturbine installation costs are still very high (approximately $2000/kW). The data in this report are from actual field installations and demonstrate significantly higher costs than for mature DG technologies.
- Fuel cell installation costs are still largely uncertain but are higher than the IC engines and CTs. The cost to install a fuel cell is around $2000/kW.

Installing a DG system generally involves the following activities:

- Project engineering
- Permitting
- Site preparation/placement
- Mechanical, including thermal recovery system
- Fuel supply system
- Electrical
- Site commissioning/startup
- Other

[51] These are costs for installation only; they do not include the generation equipment cost.
[52] Low end of the range is for diesel backup; high end is natural gas continuous duty. Size range is 1-2 MW.
[53] Low end of the range is for large systems (e.g., 25 MW) and the high end is for small CTs (1 MW) and includes heat recovery. Table 2-3 includes a summary by size.
[54] Data are for field test installations of a 30-kW microturbine. The low end of the range includes utility-donated labor. The high value includes heat recovery. Approximately $2000/kW for installation is a reasonable expectation based on field test data from the EPRI MTG Field Test Program. Preliminary results in report number 1006394 (*MTG Field Test Program: Interim Report*).
[55] These data are derived field installations.

Table 5-2 provides a component cost comparison for representative systems of each of the four DG technologies covered in this report.

Table 5-2
Representative Installation Component Cost Comparison ($/kW)

	IC Engine[56] (1.4 MW)	Combustion Turbine[57] (5 MW)	Microturbine[58] (30 kW)	Fuel Cell[59] (Representative)
Project Engineering	35	94	404	342
Permitting	-	-	44	62
Site Preparation/ Placement	88	253	244	498
Mechanical	16	63	-	86
Fuel Supply	44	-	441	252
Electrical	83	75	567	308
Site Commissioning/ Startup	14	-	20	138
Other	-	-	278	314
Total	**279**	**485**	**1998**	**2000**

Maintenance Cost Comparison

The maintenance costs for selected DG technologies are shown in **Table 5-3**. These costs represent current (2002) costs to operate and maintain the systems (excluding fuel costs). The cost to maintain the fuel cell are significantly higher that the other DG technologies.

[56] 1.4 MW continuous duty, 480V generator, fuel system, switchgear, no heat recovery.
[57] 5 MW continuous duty, no heat recovery
[58] Data are average of 2 30-kW field test installations
[59] Total is based on the average of the range from Table 5-1

Table 5-3
O&M Costs for Selected DG Technologies

	Size (kW)	O&M Cost ($/year)	O&M Cost ($/kW/year)
Microturbine	70	6250	89
PA Fuel Cell	200	46,400	232
MC Fuel Cell	250	86,000	344
IC Engine (Continuous)	1300	194,480	150
IC Engine (Peaking)	1300	72,930	56
Combustion Turbine	5500	132,000	24

Installation, Operation, and Maintenance Cost Outlook

Labor costs are anticipated to rise at roughly the escalation rate. The installation costs of ICE and CT systems should closely track the escalation rate, but the installation costs of MTG and FC systems should drop with increasing production. A good target for O&M costs is $0.01/kWh, which is the level of IC engines, CTs, and some microturbines.

A good target for installation of a DG system is $250 - $400/kW based on the installation costs of mature DG technologies and those of mature HVAC technologies for commercial buildings. Fuel cell and microturbine technologies currently fall significantly outside this range. As the technologies become more mature, their installation costs are expected to decline and could reach this level. Key factors for reaching this goal will be:

- Efficient packaging – approach “plug and play” by reducing the amount of on-site customization
- Integrated packaging – include ancillary components in the installation package (e.g., emissions control, gas compression, heat recovery, etc.)

Maintenance costs for most of the DG technologies are reasonably stable. Microturbine manufacturers are providing maintenance contracts comparable to mature technologies. However, if experience proves maintenance is required beyond the contract, the microturbine maintenance cost could increase. Fuel cells are not far enough into production to have significant data on maintenance costs. However, the estimated costs are higher than the other DG technologies. The primary factor for the fuel cell maintenance cost reduction will be the life/replacement of the fuel cell stack.

A
APPENDIX

Example Installation Cost Calculation

Below is an example for calculating the installation costs for a distributed generation system.

Distributed Generation Installation Cost Example

System Description	
Model Number	Capstone
Fuel	NG
Rating (kW)	30

Line Number (column 1)	Item (column 2)	Major/Minor Cost Component (column 3)	Labor Hours (hrs) (column 4)	Labor Rate ($/hr) (column 5)	Labor Cost ($) (column 6) col. 4 x col. 5	Materials Cost ($) (column 7)
1	**1**	***Acquisition Costs***	---	---	---	**30,000**
2	**a.**	**Engine/Generator Package**				30,000
3	**2**	***Installation Costs***		---	**29,950**	**41,646**
4	**a.**	**Project Engineering**				6,944
5	**b.**	**Permitting**				1,096
6	**c.**	**Site Preparation/Placement**				3,640
7	**d.**	**Mechanical (includes heat recovery)**	108	50	5,400	11,412
8	**e.**	**Fuel Supply System**	286	50	14,300	2,944
9	**f.**	**Electrical**	185	50	9,250	4,070
10	**h.**	**Site Commissioning/Startup**	20	50	1,000	0
11	**i.**	**Other**				11,540
12	**3**	***Total Project Costs***	**$101,956 or $3,387/kW**			

The following page includes a blank template or form that can be copied and used for preparing installation cost estimates.

Installation Cost Template

Use the form below for estimating the cost for a specific DG installation.

Distributed Generation Installation Cost Template

System Description	
Model Number	
Fuel	
Rating (kW)	

Line Number (column 1)	Item (column 2)	Major/Minor Cost Component (column 3)	Labor Hours (hrs) (column 4)	Labor Rate ($/hr) (column 5)	Labor Cost ($) (column 6) col. 4 x col. 5	Materials Cost ($) (column 7)
1	1	*Acquisition Costs*	---	---	---	
2	a.	Engine/Generator Package				
3	2	*Installation Costs*				
4	a.	Project Engineering				
5	b.	Permitting				
6	c.	Site Preparation/Placement				
7	d.	Mechanical (includes heat recovery)				
8	e.	Fuel Supply System				
9	f.	Electrical				
10	h.	Site Commissioning/Startup				
11	i.	Other				
12	3	*Total Project Costs*				

B
APPENDIX B

Example Operation and Maintenance Cost Calculation

Below is an example for calculating the operation and maintenance costs for a distributed generation system.

Distributed Generation Operation and Maintenance Cost Example

System Description	
Model Number	Engine
Fuel	Natural Gas
Operation (hr/yr)	8,000
Capacity Factor	100%
Rating (kW)	1,400

Line Number (column 1)	Item (column 2)	Major/Minor Cost Component (column 3)	Maintenance Event 1 (column 4)	Maintenance Event 2 (column 5)	Maintenance Event 3 (column 6)
1	**1**	**Maintenance Costs ($/event)**	**9,000**	**18,000**	**132,000**
2	a.	Maintenance Interval (hrs)	2,000	20,000	60,000
3	b.	Labor Hours (man hrs)	40	80	320
4	c.	Labor Rate ($/hr)	100	100	100
5	d.	Cost of Labor ($/event)	4,000	8,000	32,000
6	e.	Maintenance Materials ($/event)	5,000	10,000	100,000
Typically Provided by Manufacturer					
7	**2**	***Total O&M Costs ($/kWh)***	**0.0085**		
8	a.	Fixed O&M Cost ($/kW-yr)	0		
9	b.	Hours of Operation (hrs/year)			
10	c.	Fixed O&M Cost ($/kWh)			
11	d.	Variable O&M Cost ($/kWh)	0.0085		

Item		Calculation
1	=	1d + 1e
1d	=	1b * 1c
2	=	2c + 2d
2c	=	2a / 2b

Operation and Maintenance Cost Calculation Template

Below is a template or form for calculating the operation and maintenance costs for a distributed generation system. This can be used for estimating O&M costs for a specific application.

Distributed Generation Operation and Maintenance Cost Template

System Description	
Model Number	
Fuel	
Operation (hr/yr)	
Capacity Factor	
Rating (kW)	

Line Number (column 1)	Item (column 2)	Major/Minor Cost Component (column 3)	Routine Maintenance (column 4)	Top-end Overhaul (column 5)	Major Overhaul (column 6)
1	1	Maintenance Costs ($/event)			
2	a.	Maintenance Interval (hrs)			
3	b.	Labor Hours (man hrs)			
4	c.	Labor Rate ($/hr)			
5	d.	Cost of Labor ($/event)			
6	e.	Maintenance Materials ($/event)			
Typically Provided by Manufacturer					
7	2	*Total O&M Costs ($/kWh)*			
8	a.	Fixed O&M Cost ($/kW-yr)			
9	b.	Hours of Operation (hrs/year)			
10	c.	Fixed O&M Cost ($/kWh)			
11	d.	Variable O&M Cost ($/kWh)			

Item		Calculation
1	=	1d + 1e
1d	=	1b * 1c
2	=	2c + 2d
2c	=	2a / 2b

C
APPENDIX C

Location Factors

Table C-1
Location Factors for Selected Cities

State	City	Materials	Installation	Total
Nation	Average	100.0	100.0	100.0
Alabama	Birmingham	96.6	72.3	84.9
Alaska	Anchorage	132.3	119.4	126.1
Arizona	Phoenix	100	78.3	89.6
California	San Francisco	110.7	139.3	124.4
California	Los Angeles	104.9	117.9	111.2
Colorado	Denver	101.9	84.8	93.7
D.C.	Washington	99.4	91.3	95.5
Georgia	Atlanta	97.1	79.7	88.7
Illinois	Chicago	98	124.3	110.6
Kansas	Kansas City	98	88.5	93.4
Massachusetts	Boston	104.2	130.2	116.7
Minnesota	Minneapolis	98.6	122.8	110.2
New Jersey	Newark	104.3	122	112.8
New York	New York	109.1	161.3	134.2
Texas	Dallas	99.6	72.3	86.5
Washington	Seattle	106	104.8	105.5

Source: Means Mechanical Cost Data

The location factors in this table can be used to adjust material and location costs depending on location.

Table C-2
Labor Rate Cost Indexes for Selected Cities

State	San Francisco	Atlanta	Newark	Kansas City
Site Work	113.4	94.6	102.7	92
Concrete Formwork	141.6	76.8	126.4	82.8
Mechanical	171.4	77.4	124.8	87.1
Electrical	146.7	84.1	130.9	94.5

This table shows an example of how the labor costs vary by city and type of activity.

D
APPENDIX D

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E
APPENDIX E

Model Number Cross-Reference

IC Engines	
ICE1	Gas generator set for continuous duty - Caterpillar G3516B Engine Genset, NG fuel, 1.3-MW
ICE2	Gas generator set for prime power - Caterpillar G3516B Engine Genset, NG fuel, 1.4 MW
ICE3	Gas power module for peaking power - Caterpillar G3516B Power Module, NG fuel, 1.25 MW
ICE4	Diesel generator set for standby power - Caterpillar 3516B Engine Genset, Diesel fuel, 2.0 MW
ICE5	Diesel generator set for standby power - Cummins DQKC Engine Genset, Diesel fuel, 2.0 MW
Combustion Turbines	
CT1	Solar Turbines Saturn 20 combuston turbine, NG, 1.2 MW
CT2	Dresser KG2-3E combuston turbine, NG, 1.9 MW
CT3	Centrax CX501-KB5 with Allison 501 combuston turbine, NG, 3.8 MW
CT4	Solar Turbines Taurus 60 combuston turbine, NG, 5 MW
CT5	Centrax CX501-KB7 with Allison 501 combuston turbine, NG, 5.1 MW
CT6	Centrax CX501-KH5 with Allison 501 combuston turbine, NG, 6.3 MW (with HRSG and steam injection into the combustion casing)
CT7	GE LM2500 combuston turbine, NG, 23.3 MW

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Emerging Distributed Resource Technologies

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